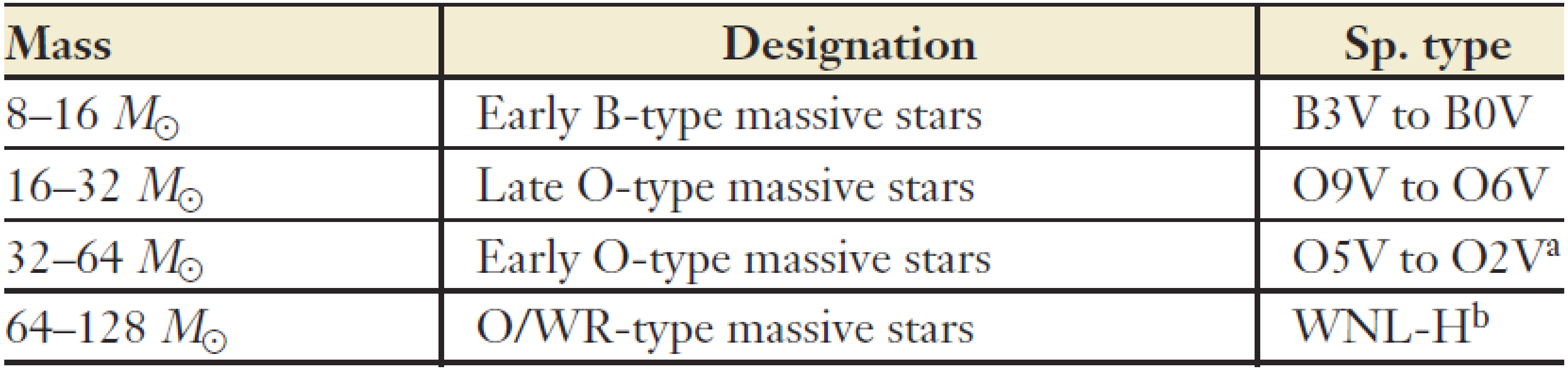
Star formation

The formation of massive stars

Massive stars



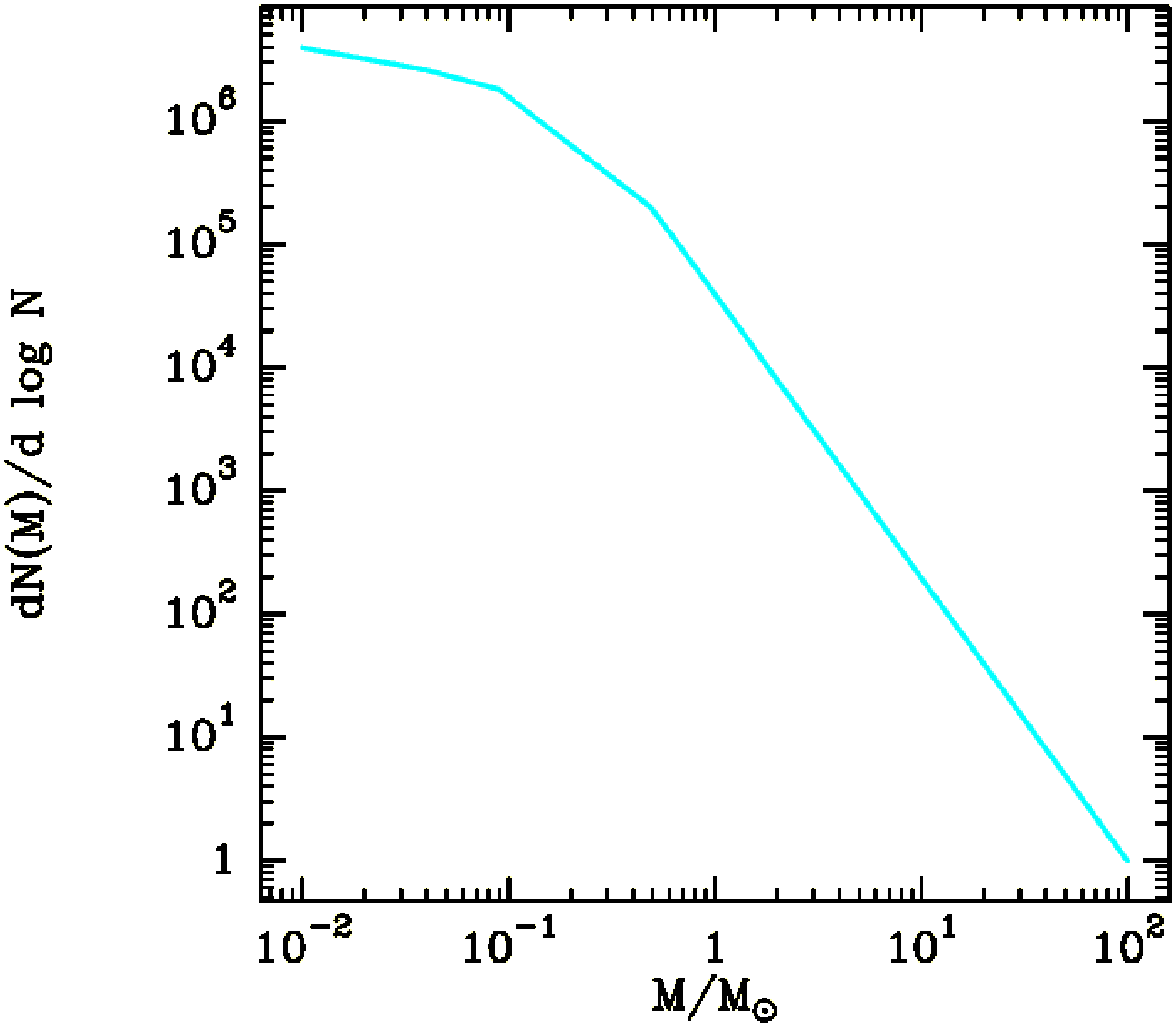
Mass	Designation	Sp. type
8–16 $M_\odot$	Early B-type massive stars	B3V to B0V
16–32 $M_\odot$	Late O-type massive stars	O9V to O6V
32–64 $M_\odot$	Early O-type massive stars	O5V to O2V[a]
64–128 $M_\odot$	O/WR-type massive stars	WNL-H[b]

They are

- rare
- have a wild life wasting their resources mindlessly,
- die young.

But: They dominate the luminosity!

Initial mass function



In main slope of Salpeter IMF:

$$\frac{dN(M)}{d\log M} \propto M^{-1.35}$$

$$\rightarrow$$

$$N(1\mathrm{M}_o) = 100 \times N(30\mathrm{M}_o)$$

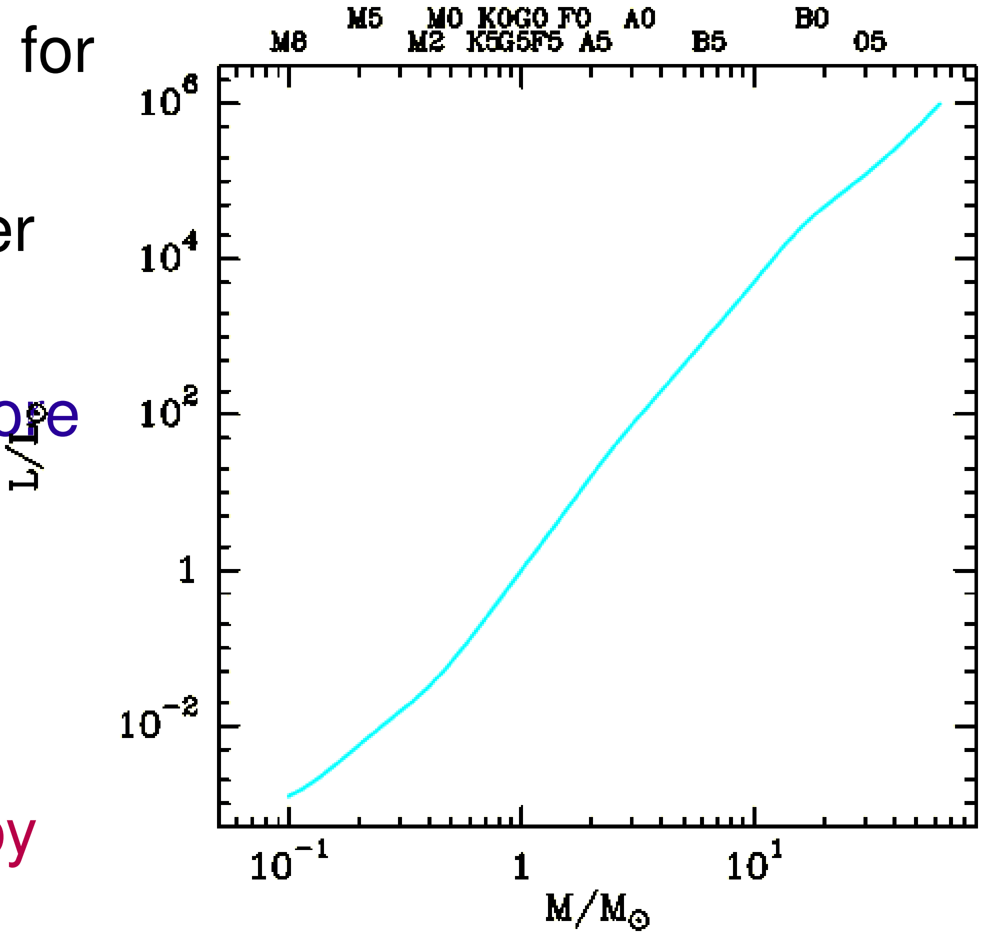
Initial mass function

- 100 stars with 1 $M_\odot$ are created for each star with 30 $M_\odot$
- 1 $M_\odot$ stars live 2000 times longer than 30 $M_\odot$ stars

⇨ at any time there are **2×10^5** more stars with 1$M_\odot$ than with 30 $M_\odot$

But: $L(30\ M_\odot) = \mathbf{1.3\times10^6}\ L(1\ M_\odot)$

⇒ total luminosity is dominated by high mass stars



...and that doesn't even take mechanical energy (stellar winds, supernovae) into account!

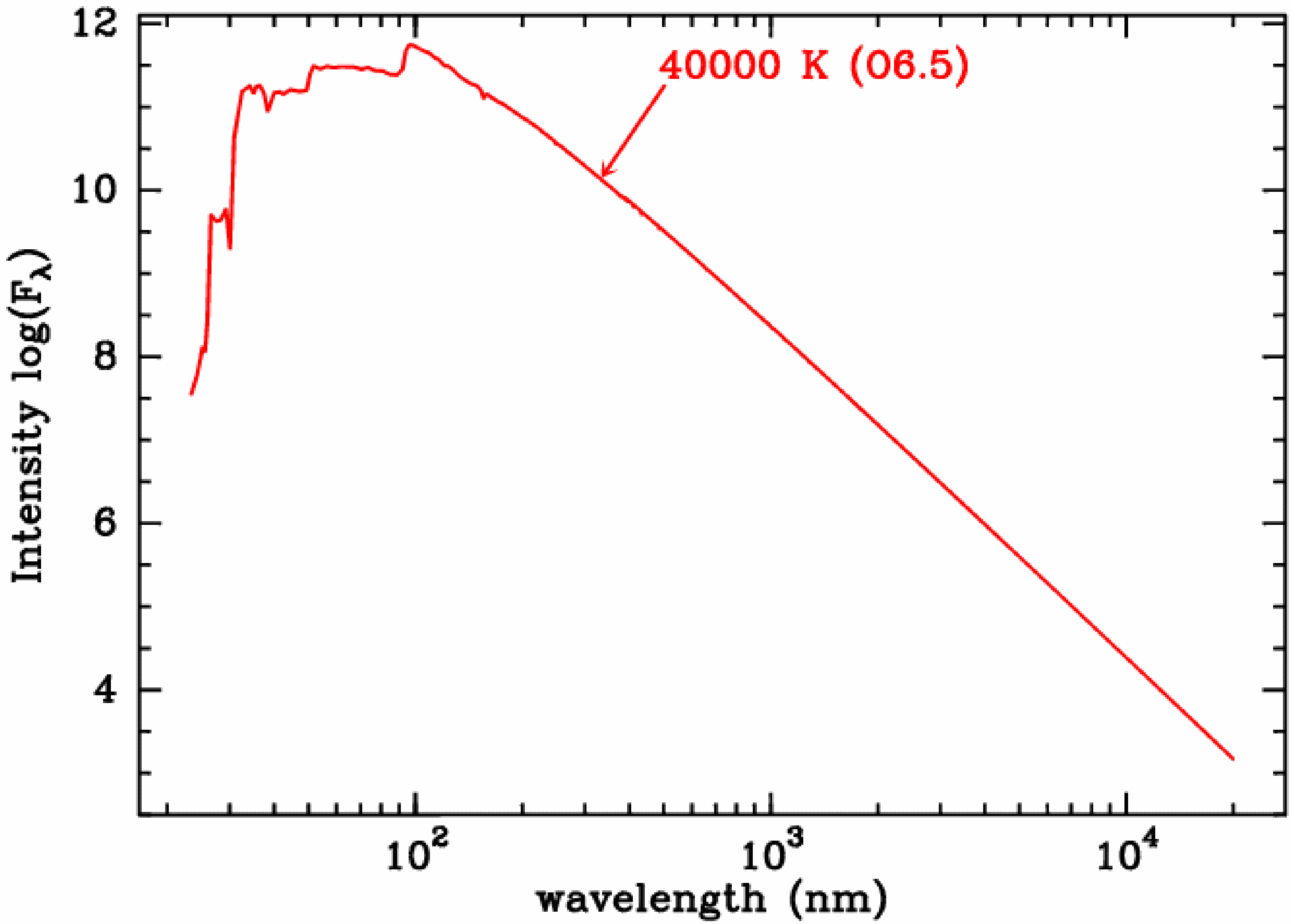
Massive stars

- As a consequence of the IMF massive stars only exist in clusters with thousands of other stars.

- Cluster appearance dominated by the OB stars.

Comparison of 30Dor in the LMC, NGC3603, the brightest cluster in the Milky Way, and the prominent Trapezium cluster in Orion. O stars dominate the images (Zinnecker & Yorke 2007)

Stellar spectra



Only high mass stars produce enough UV to create HII regions

Radiative impact

Ionization of surroundings:

- compact/ultracompact/hypercompact HII regions

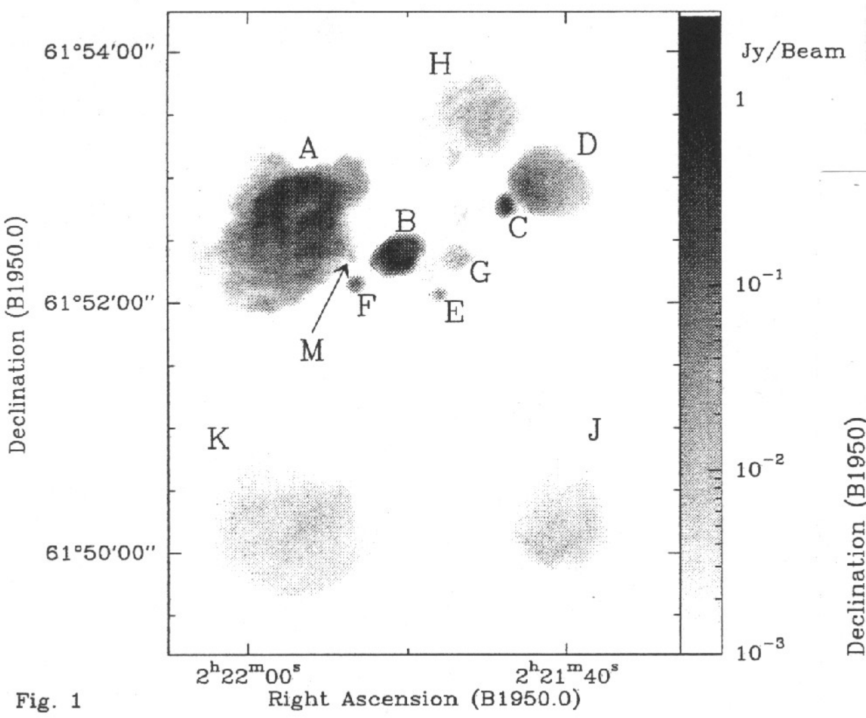
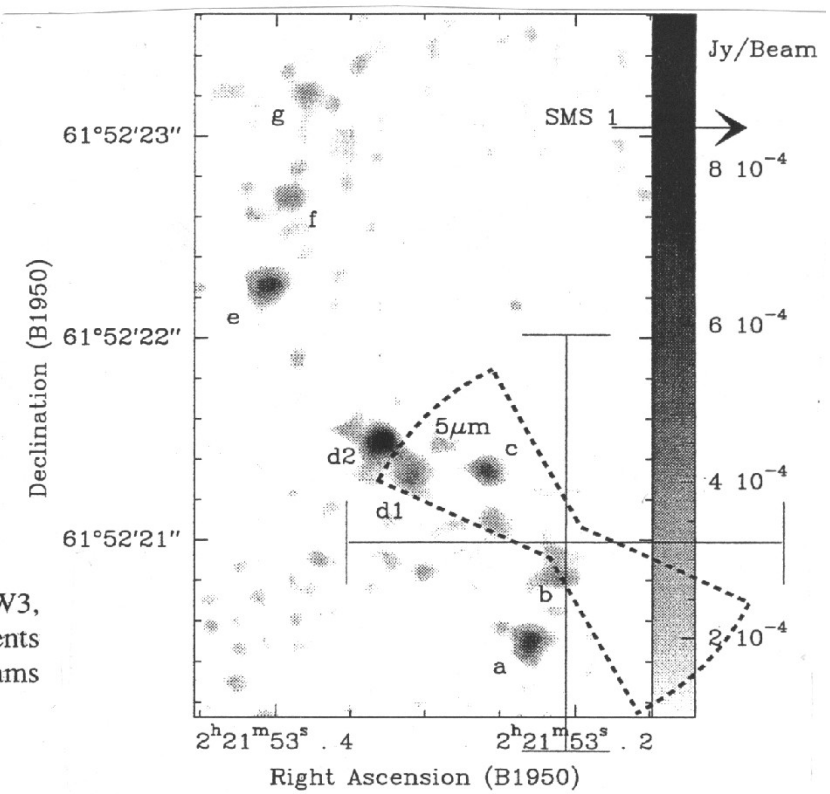


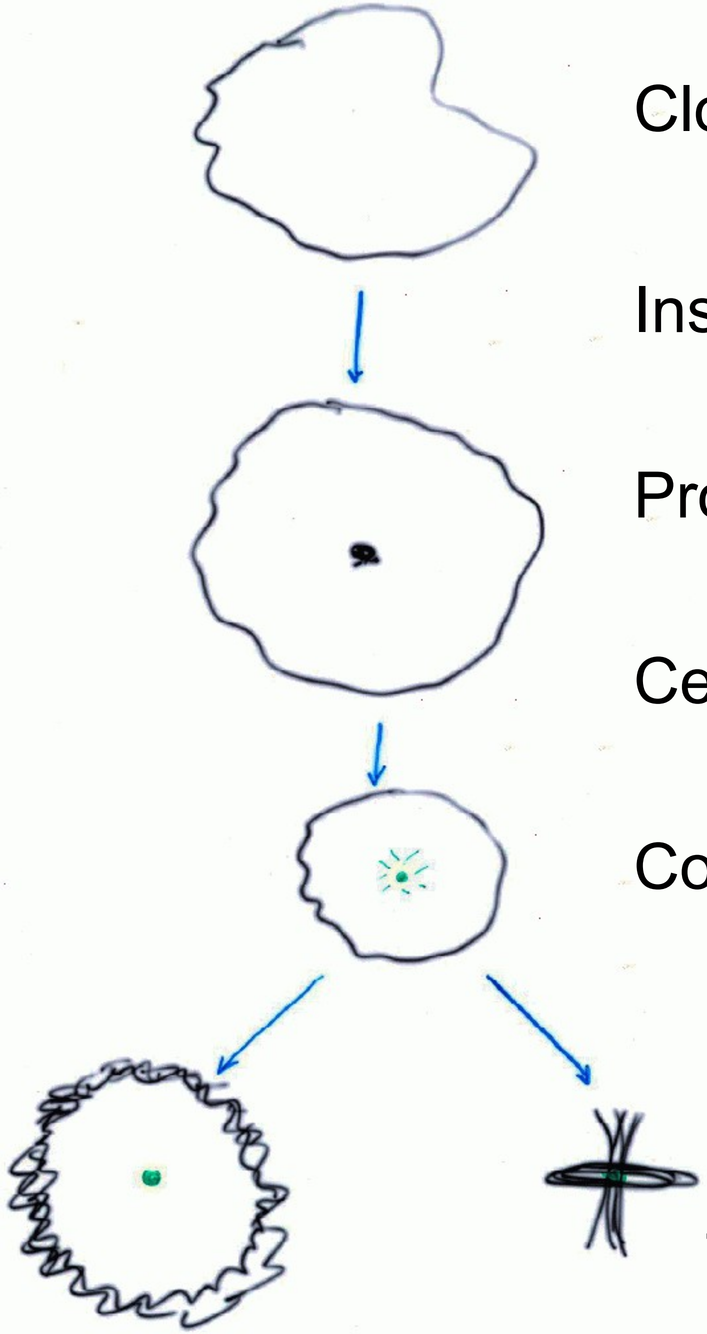
Fig. 1. A gray-scale representation of a 6 cm continuum image of W3, with a FWHM beam size of 3.″38 by 2.″72. Continuum components have been labeled following the scheme introduced by Wynn-Williams (1971) and Harris & Wynn-Williams (1976).



Tieftrunk et al. (1997)

Global star-formation picture

Interaction of infall and radiation:



Cloud with $M > M_J$

Inside-out collapse: 10^6a

Protostellar core

Central collapse: 10^5a

Cocoon star

$M > 3M_\odot$: 10^6a

BN object with HII

$M < 3M_\odot$: 10^7a

T Tau star

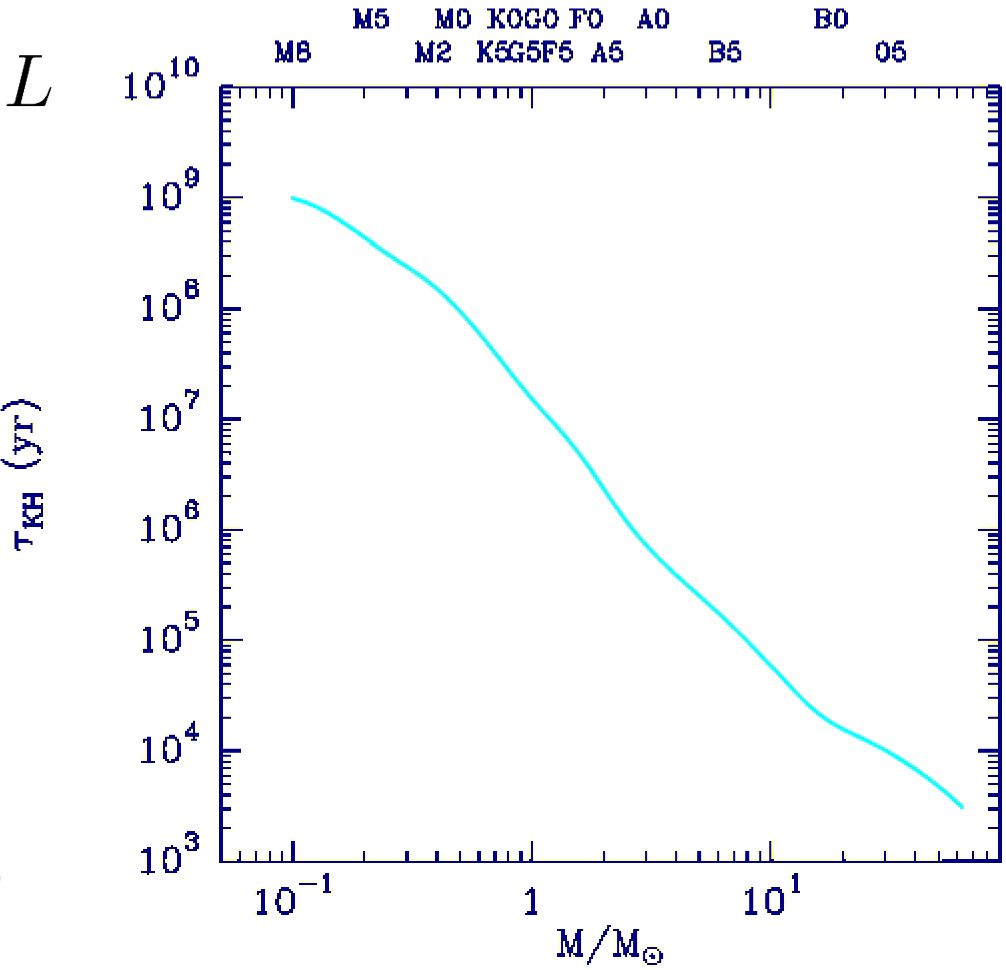
Repetition: Low mass stars

- Protostars
  - Still accreting
  - Luminosity mainly accretion luminosity
  - Not visible in the optical
- Pre-main sequence (PMS) Stars
  - Not accreting any more
  - Gravitational energy contributes to luminosity
  - Visible in the optical (envelope dispersing)
- ZAMS Stars
  - Luminosity through nuclear reactions

High mass stars

- Definition: $\tau_{HK} < \tau_{acc}$
  - Helmholtz-Kelvin timescale
    - Time to radiate gravitational energy away:

$$\tau_{HK} = \frac{GM^2}{2R} / L$$



    - Mass-luminosity relation:

$$L \propto M^{3.2}$$

    - Mass-size relation:

$$R \propto M^{0.6}$$

    - Resulting timescale:

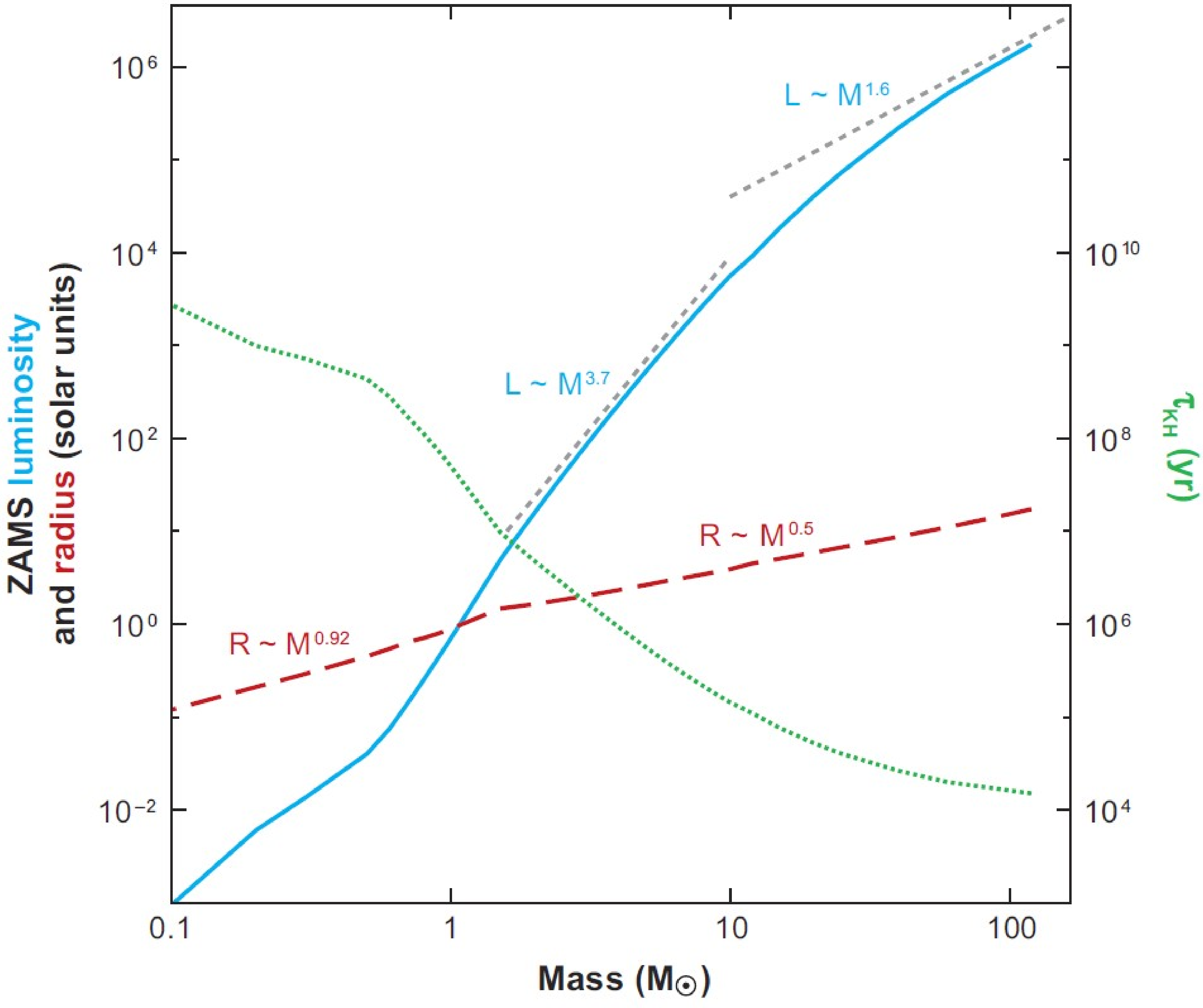
$$\tau_{HK} \propto M^{-1.8}$$

Kelvin-Helmholtz timescale

More detailed computations using ZAMS functions:

- Break in zero-age luminosity function around 10 $M_\odot$
- Break in mass-size relation around 1.5$M_\odot$

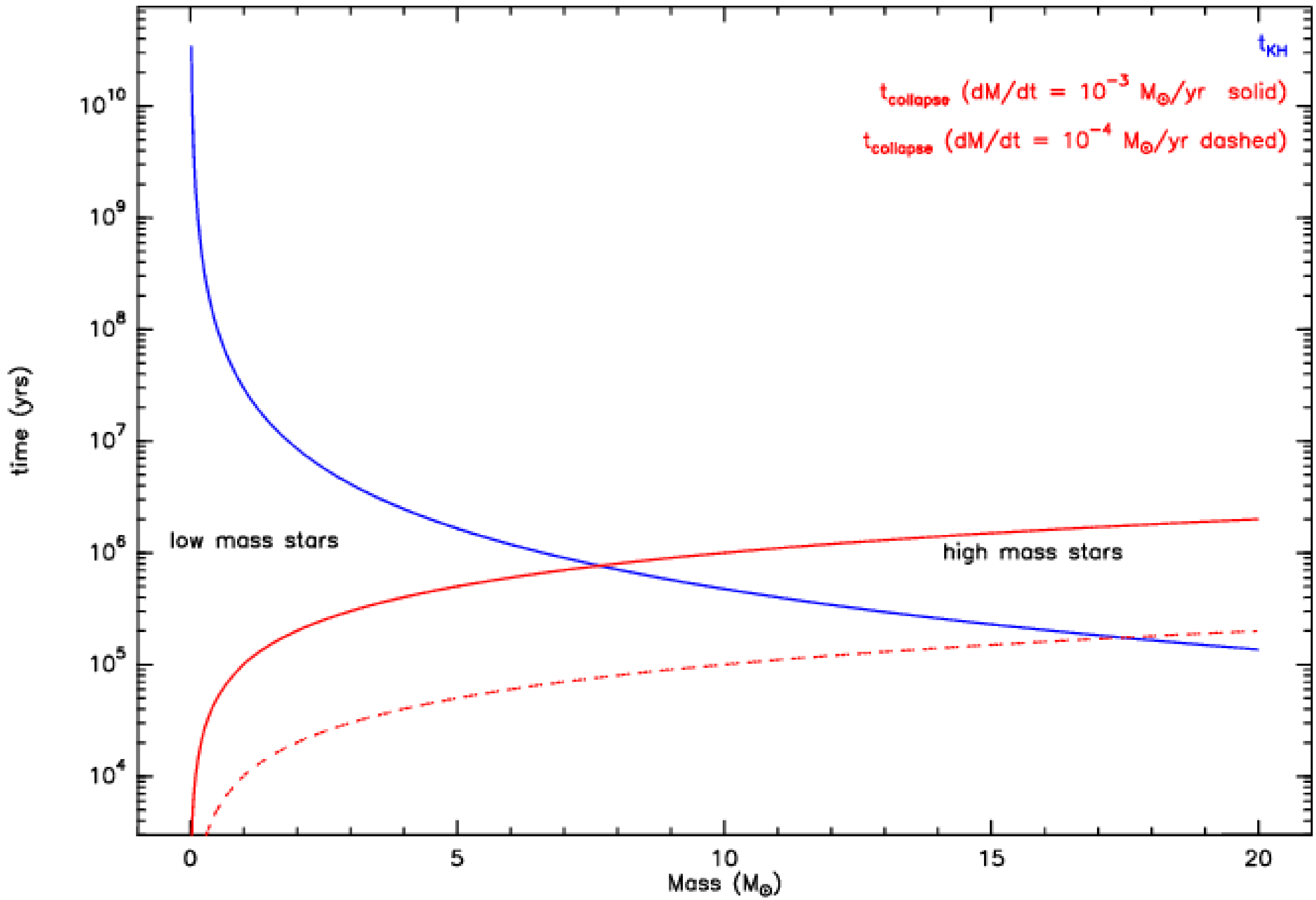
Zinnecker & Yorke (2007)



Kelvin-Helmholtz timescale

- Determines prestellar contraction time:
  - Typical accretion rate $10^{-5}\ M_\odot/a$
  - Accretion time:
    - $\tau_{acc} \sim 10^5$ a for 1 $M_\odot$ star
    - $\tau_{acc} \sim 10^6$ a for 10 $M_\odot$ star
  - K-H timescale: time for contraction
    - 10^7 a for 1 $M_\odot$ star > τ_{acc}: long pre-main sequence phase
    - 10^5 a for 10 $M_\odot$ star < τ_{acc}: no pre-main-sequence phase

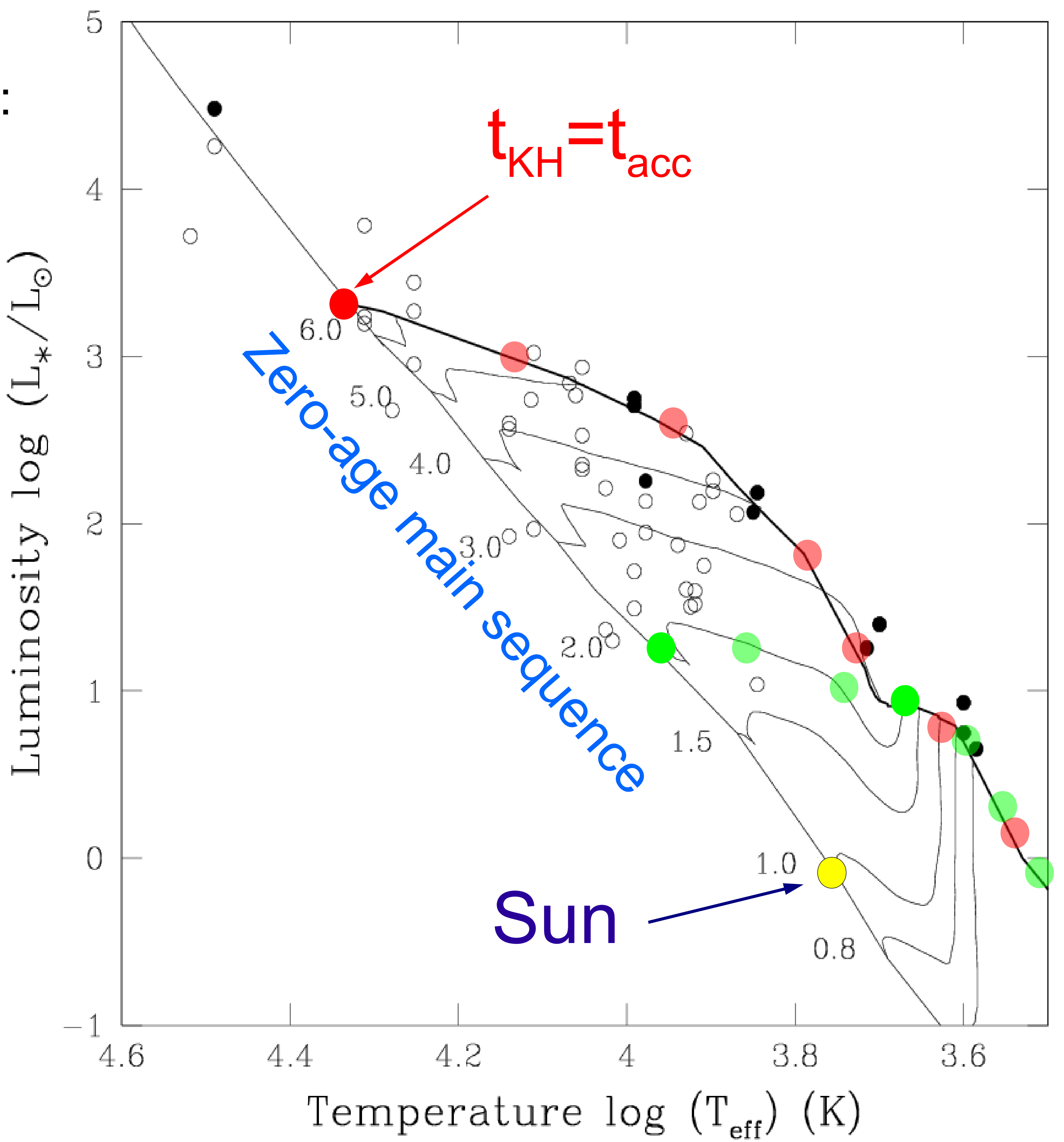
Kelvin-Helmholtz timescale



Stars > 8 $M_\odot$ ignite before the collapse/accretion is finished

Palla & Stahler (1990):

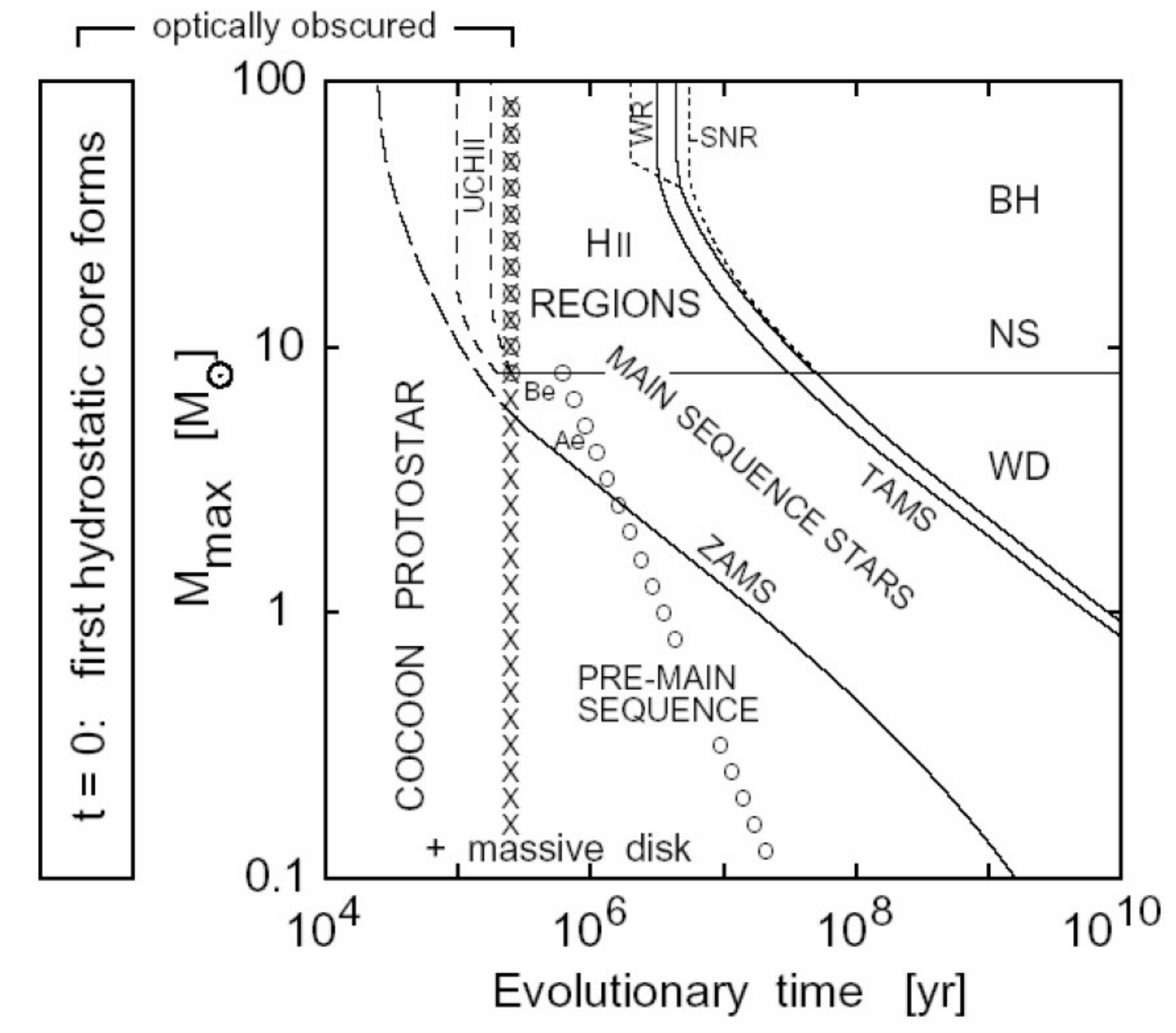
dM/dt=10^{-5} M_o/yr



Massive stars are born on the Main Sequence!

There are no high mass pre-main sequence stars

Stellar evolution tracks



Yorke (1998)

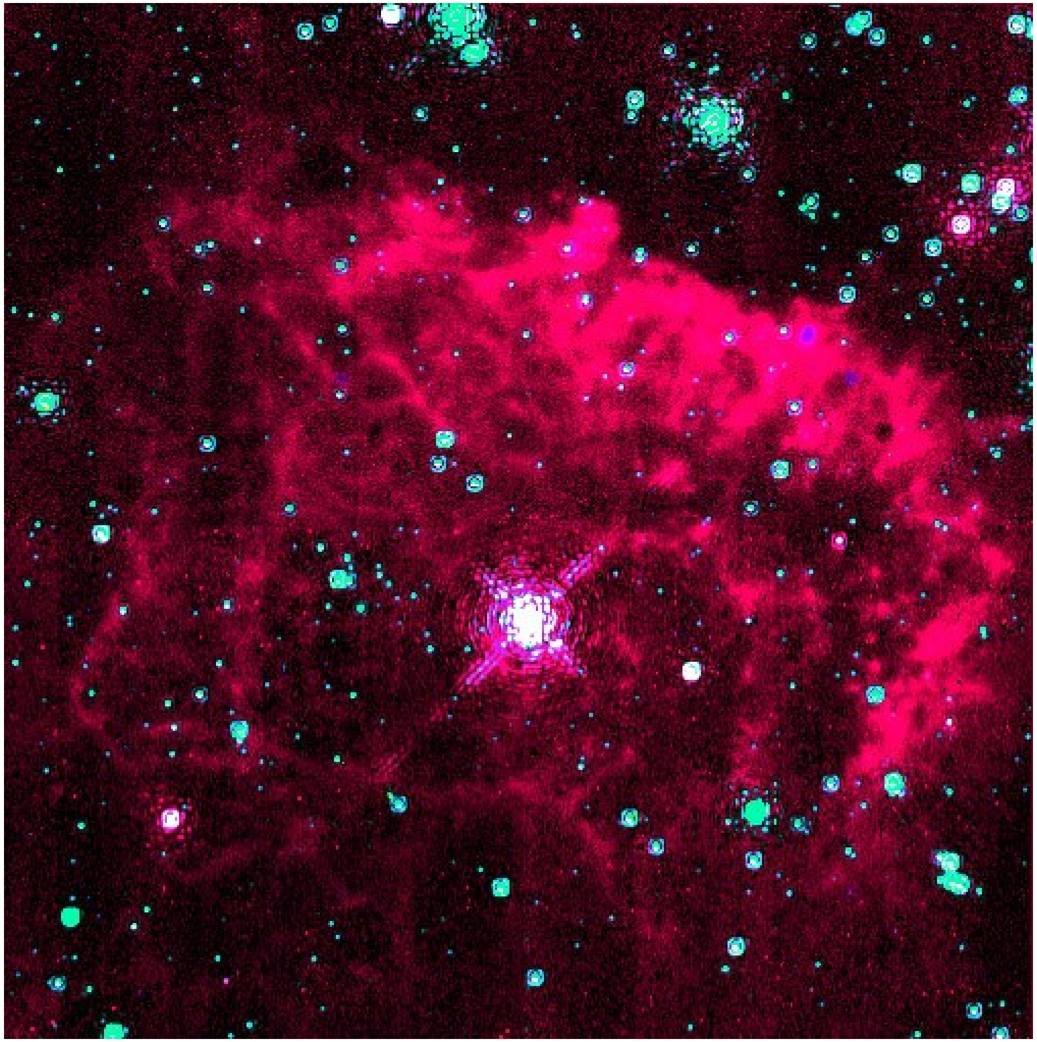
- Stars more massive than 8 $M_\odot$ hit the main sequence while accreting
- High mass stars are born embedded in a dense molecular core → No direct observations of young massive protostars

- Massive stars have a short life: $t(1M_o) = 2000 \times t(30M_o)$
- But: High mass protostars are even rarer than high mass stars by a factor of about 200

How massive can stars get?

Pistol star

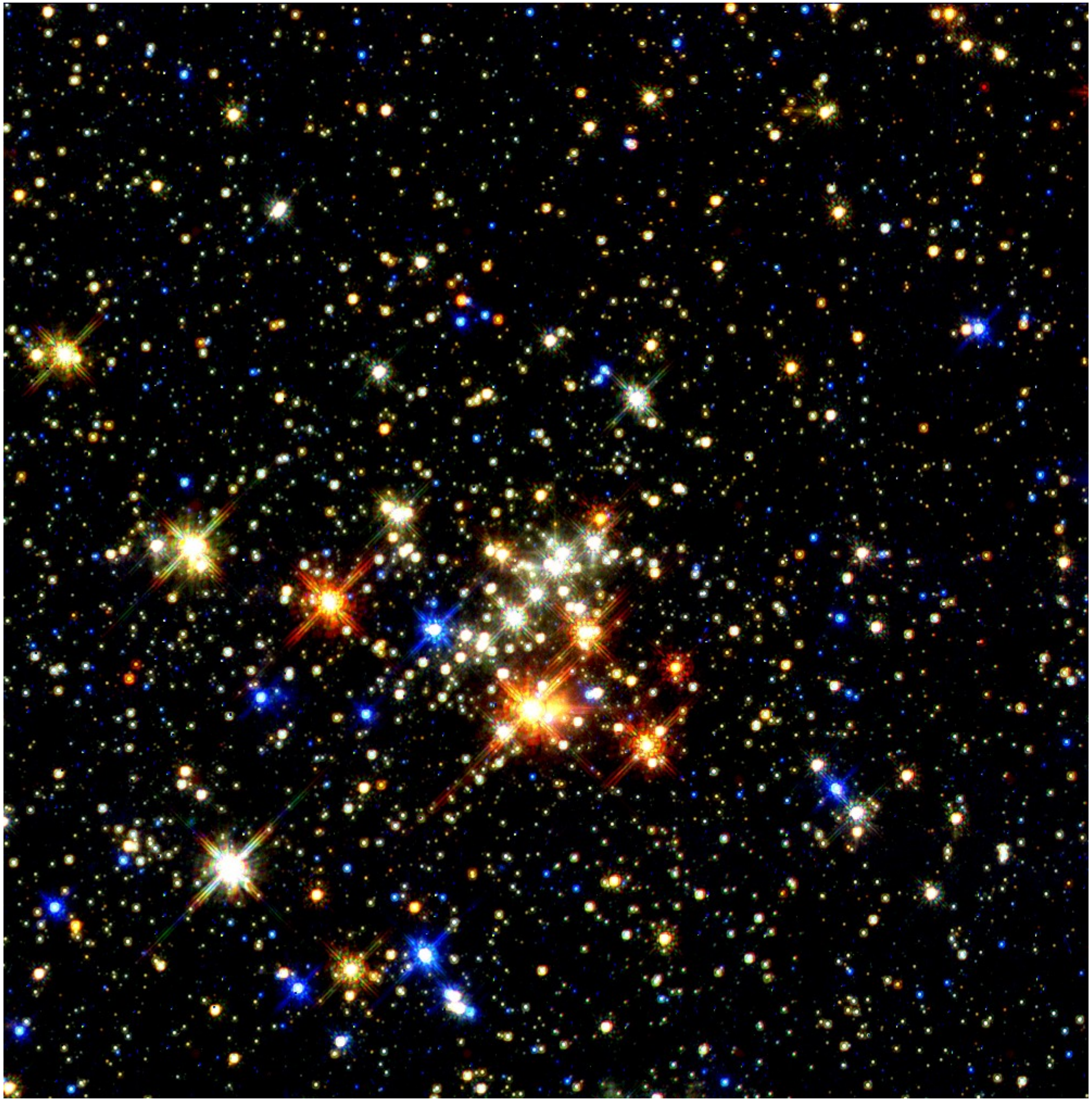
- Most massive known star in our Galaxy
- Luminous Blue Variable
- Initial Mass 150-250 $M_\odot$
- Luminosity 10^7 $L_\odot$
- Age 2 Ma
- In Pistol nebula :
  - diameter 1 pc
  - Mass 10 $M_\odot$



How massive can stars get?

Pistol star

- In Quintuplett cluster
  - Galactic center region
  - Age 4 Ma
  - Mass ≈ 10^4 $M_\odot$



How massive can stars be?

The Eddington limit:

- Equilibrium between gravitational pressure and radiative pressure

$$\frac{dp}{dr} = -G\frac{M\rho}{r^2} \qquad\qquad \frac{dp}{dr} = -\frac{\kappa\rho}{c}\frac{L}{4\pi r^2}$$

  - independent of r
  - κ = opacity = extinction cross section/mass
    - $\kappa = \sigma_T/m_P$ for electron scattering in ionized gas,
      - σ_T - Thompson scattering cross section

→ Stars with $L > L_{\mathrm{Edd}} = \frac{4\pi G M m_P c}{\sigma_T} = 3.2\times10^4 \left(\frac{M}{M_\odot}\right) L_\odot$

are not stable.

→ Mass loss rates of 10^{-4}-10^{-3} $M_\odot$/a observed for stars with > $30M_\odot$.

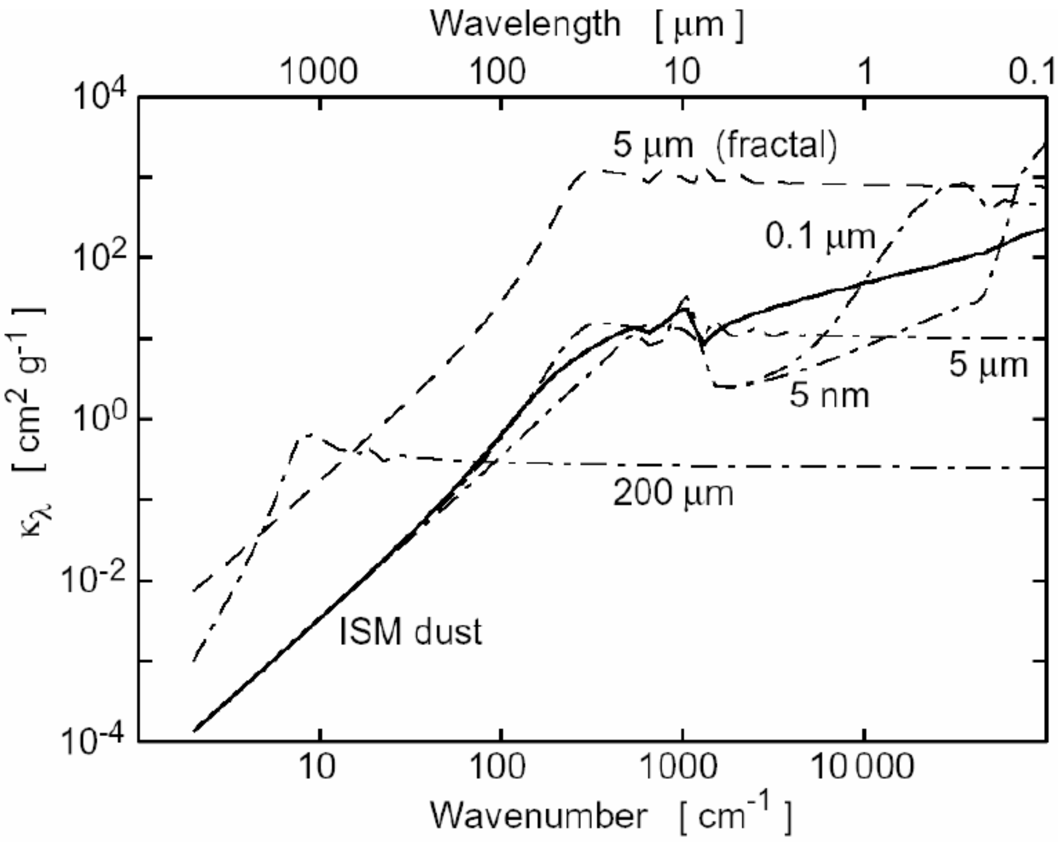
→ Stars with $L/M > 80000 L_\odot/M_\odot$ → $M > 200M_\odot$ will be disrupted.

How massive can stars become?

The accretion dilemma:

- Radiative pressure on accreting material dominated by dust
  - Good dynamic coupling between gas and dust ($\tau_c \sim 150$a)
  - Dust opacity >> neutral gas opacity
  - Effective opacity weighted by stellar spectrum = Planck average

$$\kappa_P(T_*)L = \int_0^\infty \kappa_\nu L_\nu(T_*)d\nu$$

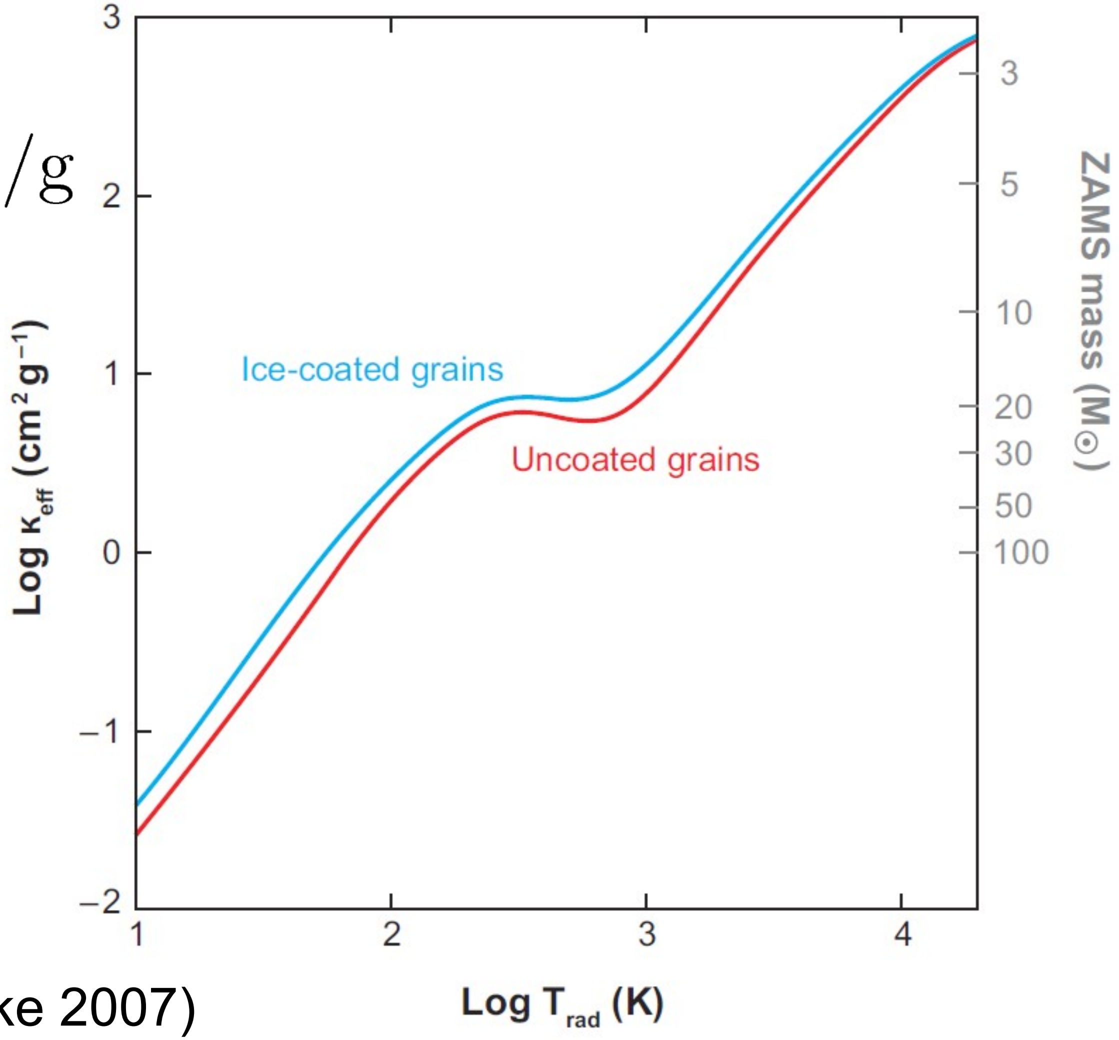


Typical dust opacities (Yorke 2004)

The accretion dilemma

$$\kappa_P(T_*)L = \int_0^\infty \kappa_\nu L_\nu(T_*)d\nu$$

- Planck average opacity:
  - Opacity grows with radiation temperature
  - $\kappa_P(6000\mathrm{K}) \approx 150\mathrm{cm}^2/\mathrm{g}$
  - Hotter stars give higher radiation pressure



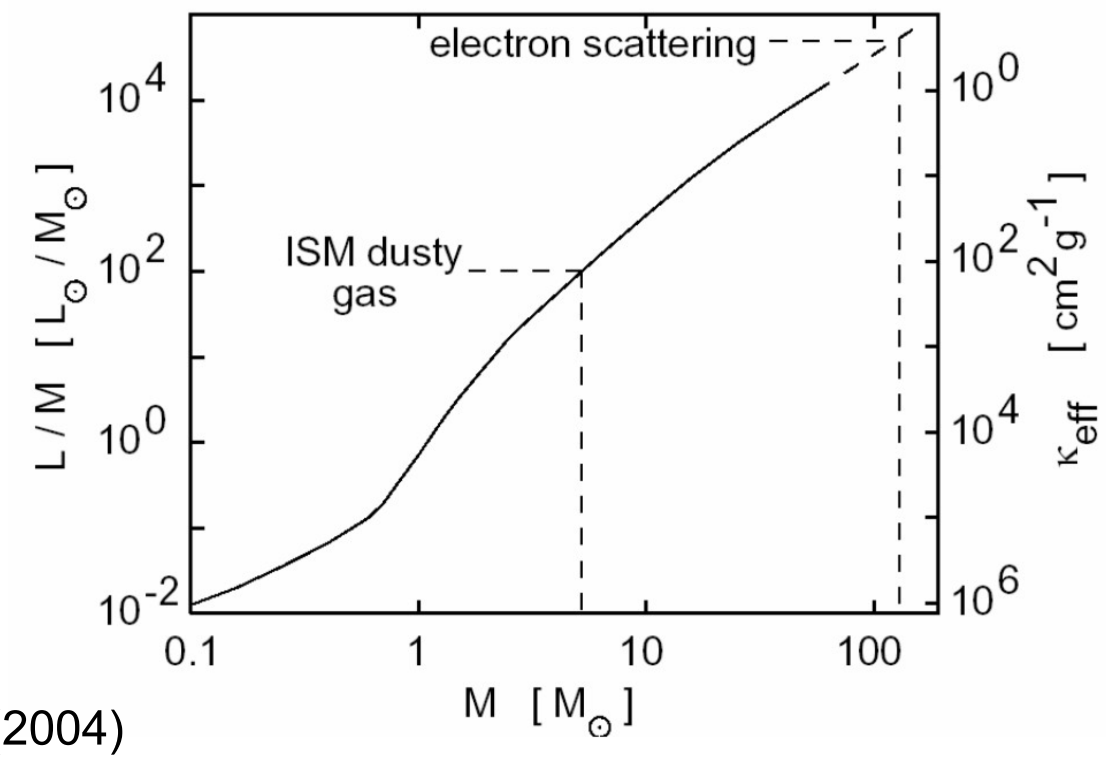
Planck opacities (Zinnecker & Yorke 2007)

Figure 6

The accretion dilemma

- Flow of material onto the protostar is only maintained if accretion flow (due to gravitational pressure) exceeds radiation pressure (at dust sublimation radius)
- Stars with $L/M > 100L_\odot/M_\odot$, $M > 8M_\odot$ cannot accrete any more

→ It is impossible to form massive stars by homogeneous accretion!

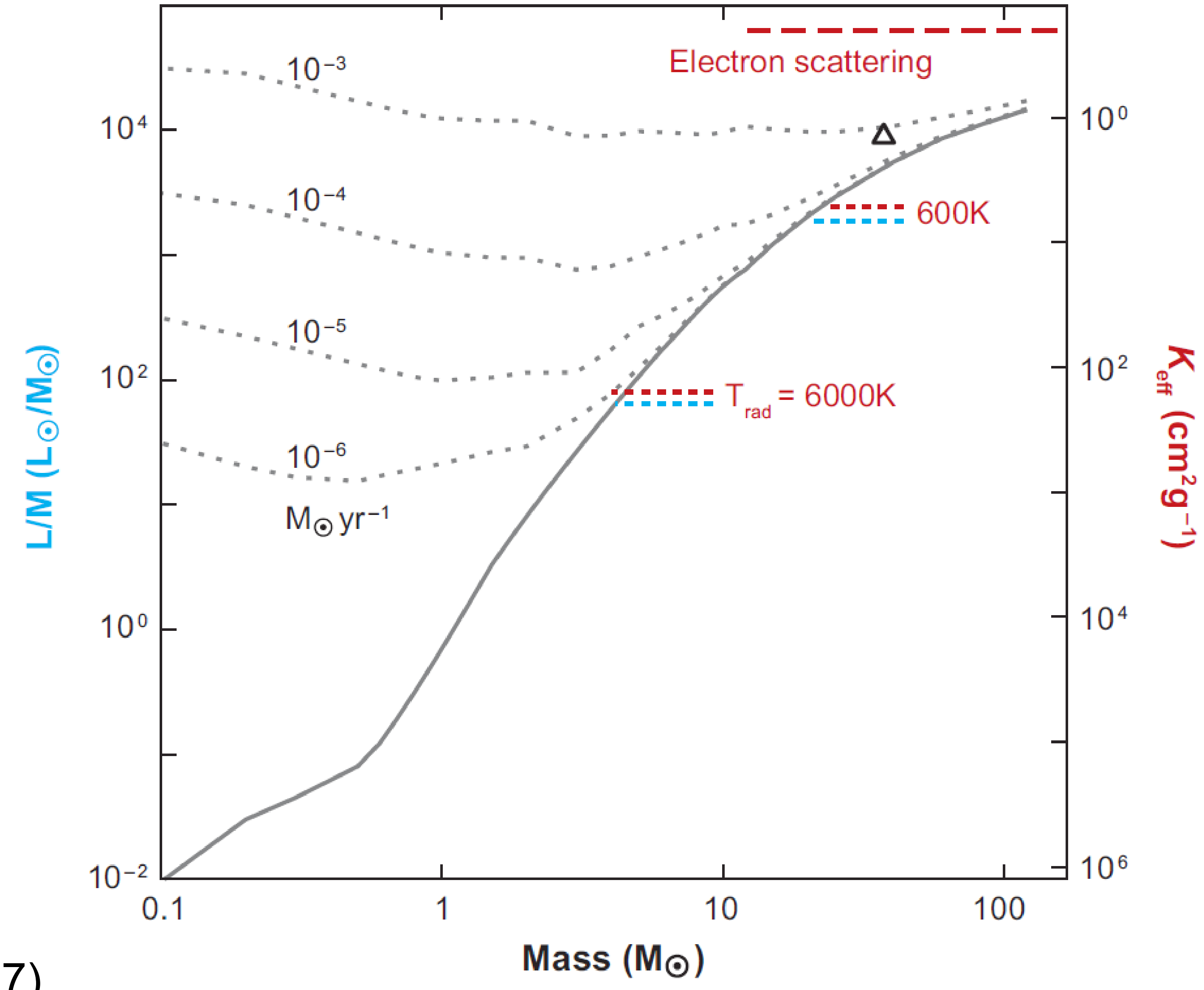


Yorke (2004)

The accretion dilemma

More detailed computations:

- Higher limit if effective temperature of the protostar is lowered
- Continued growth if higher accretion flow can be maintained
  - Typical rates: $10^{-5}\ M_\odot/a$



Zinnecker & Yorke (2007)

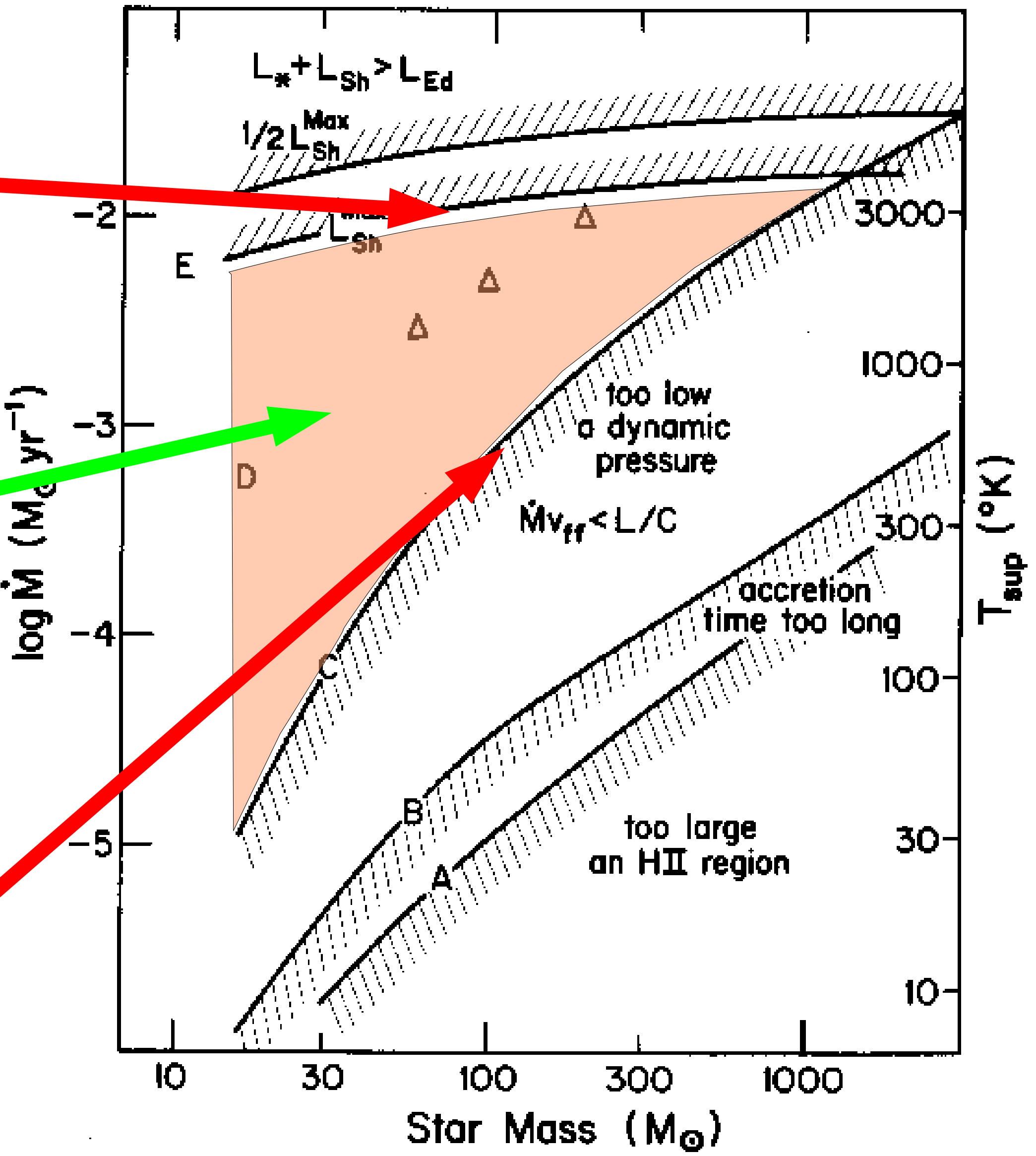
Figure 5

Accretion limits

forbidden:
Eddington limit:
(radiation pressure blows away stellar envelope)

allowed region

forbidden:
Kahn limit:
(radiation pressure blows away infalling dust)



The accretion dilemma

- For standard accretion rates (10^{-5} $M_\odot$/a) stars more massive than 8 $M_\odot$ cannot form.
- Extreme accretion rates need to be maintained to create stars as massive as 30 $M_\odot$.
- For very massive stars, the time to form would also be much longer than the main sequence lifetime!

- The formation of massive stars cannot be explained as a scaled-up version of low-mass star formation!
- Is it possible to maintain high accretion rates?

Proposed solutions

- Monolithic collapse (like low mass stars)
  - through disk
  - turbulent medium (higher accretion rates)
  - changed dust properties
- Competitive accretion
  - Dynamics of Stars in Molecular Cloud
  - Mass gain through Bondi-Hoyle accretion
    - The rich get richer
    - Location, location, location
- Coagulation
  - merging of (less) massive (proto)stars

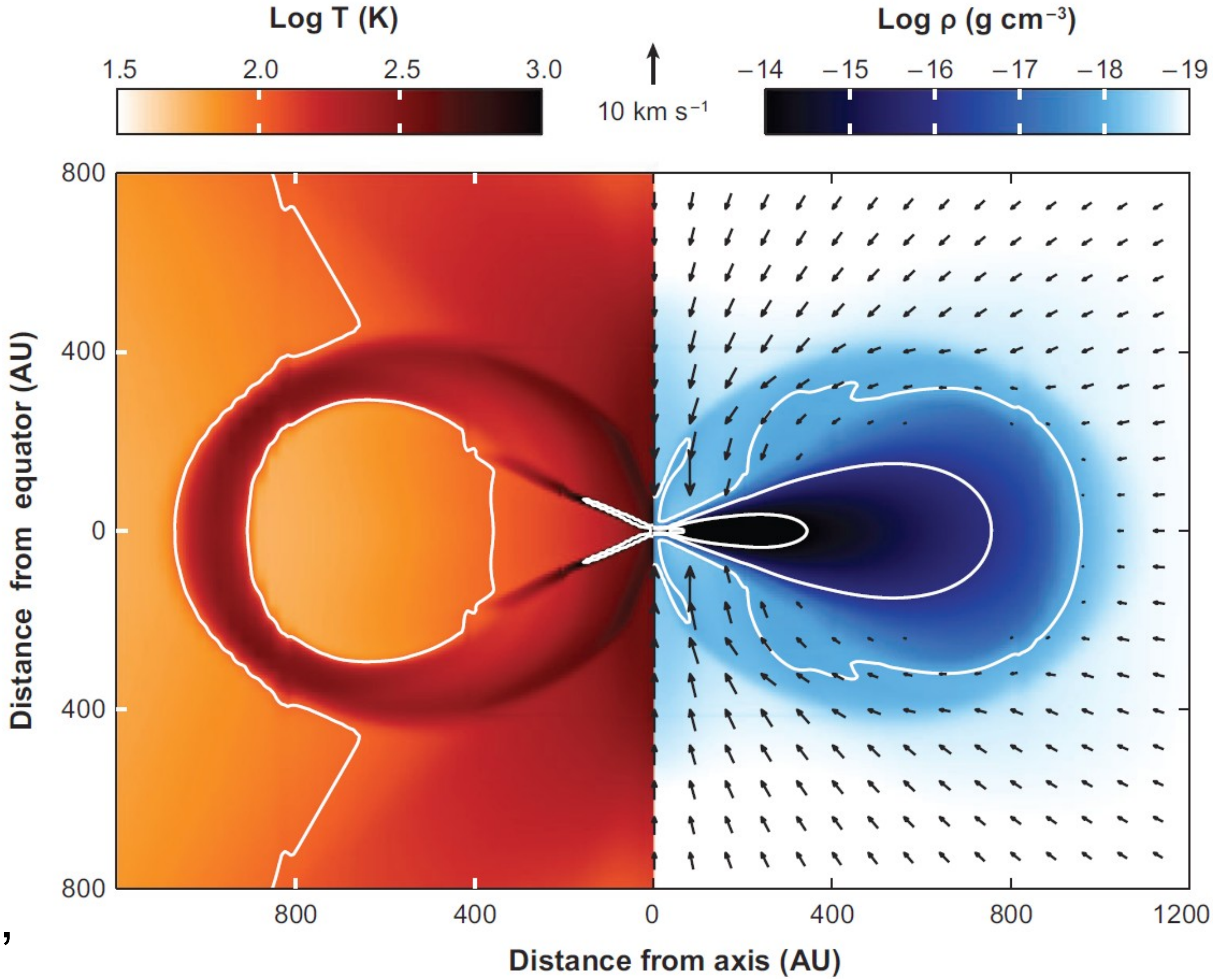
Ongoing debate

Monolithic collapse?

Initial collapse creates self-shielding disk:

- Radiative pressure lowered by factor > 30 in disk plane

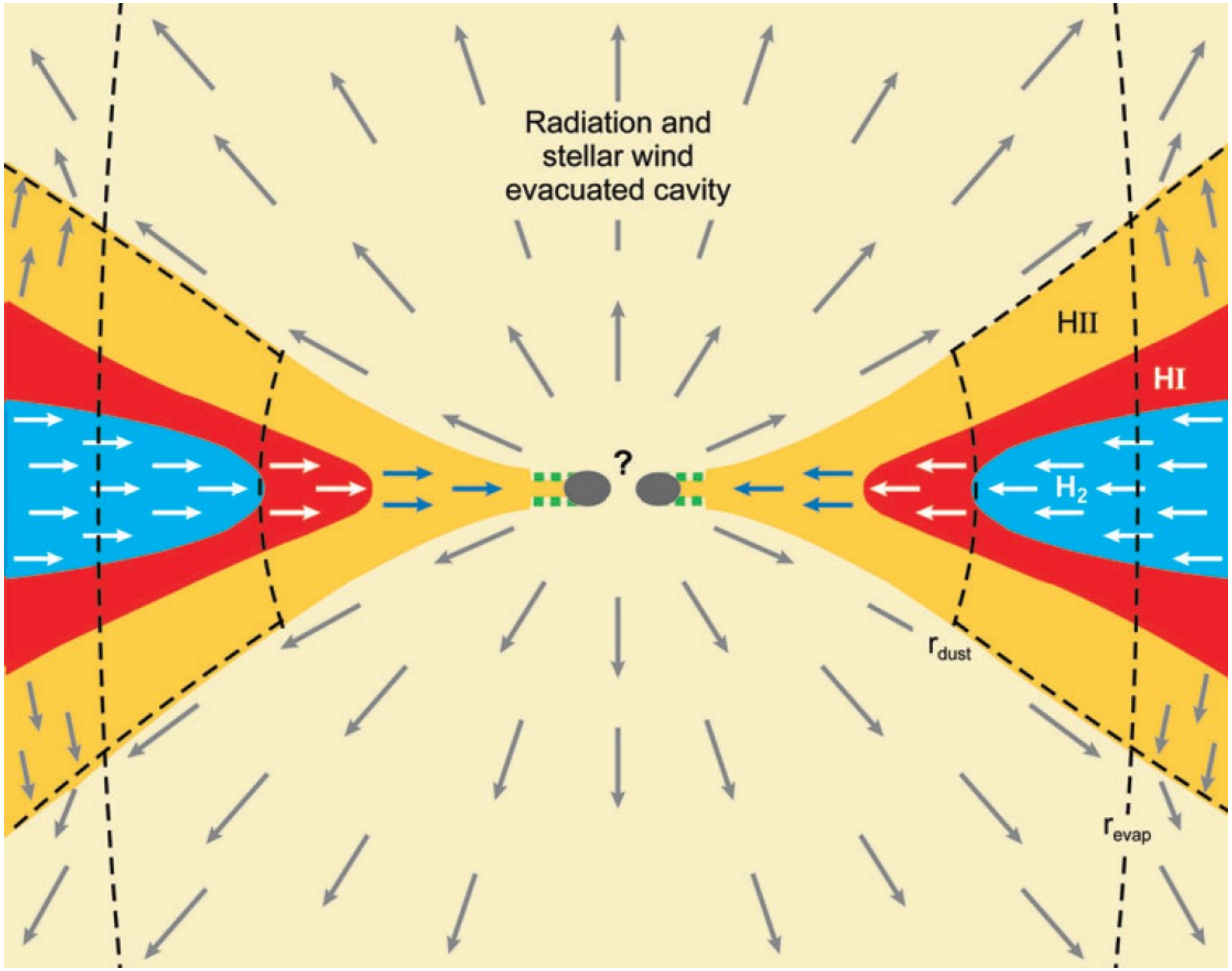
Edge-on structure of a massive accreting protostar and envelope 65000a after the formation of the protostellar core:



$7M_\odot$ are in the protostar,
$2.8M_\odot$ in the disk and
$0.2M_\odot$ in the envelope (Yorke & Bodenheimer 1999)

Monolithic collapse?

Combination of accretion and wind:

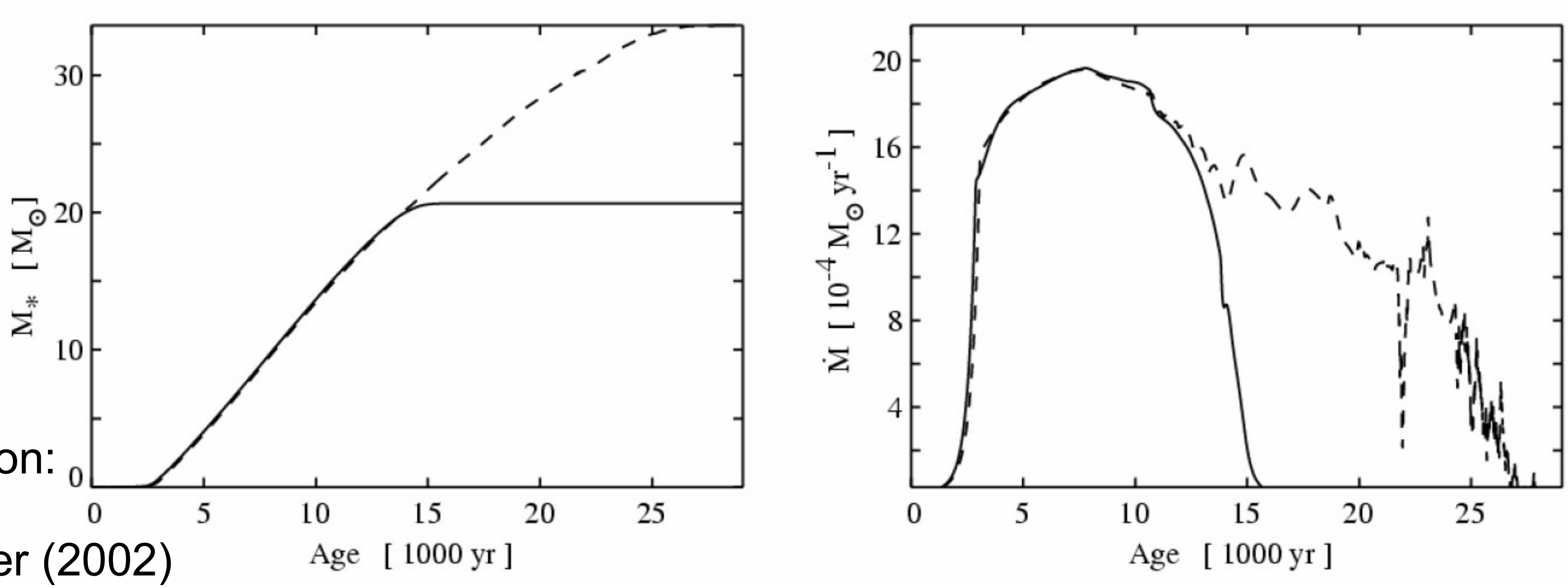


- Inflow in the equatorial plane
- High mass infall rate maintained in disk
- Polar cavity excavated by radiation pressure and stellar winds

Zinnecker & Yorke (2007)

Monolithic collapse?

Details of radiative transfer (effective opacity κ_P) and support of accretion rate by available core mass determines eventual accretion and stellar growth:

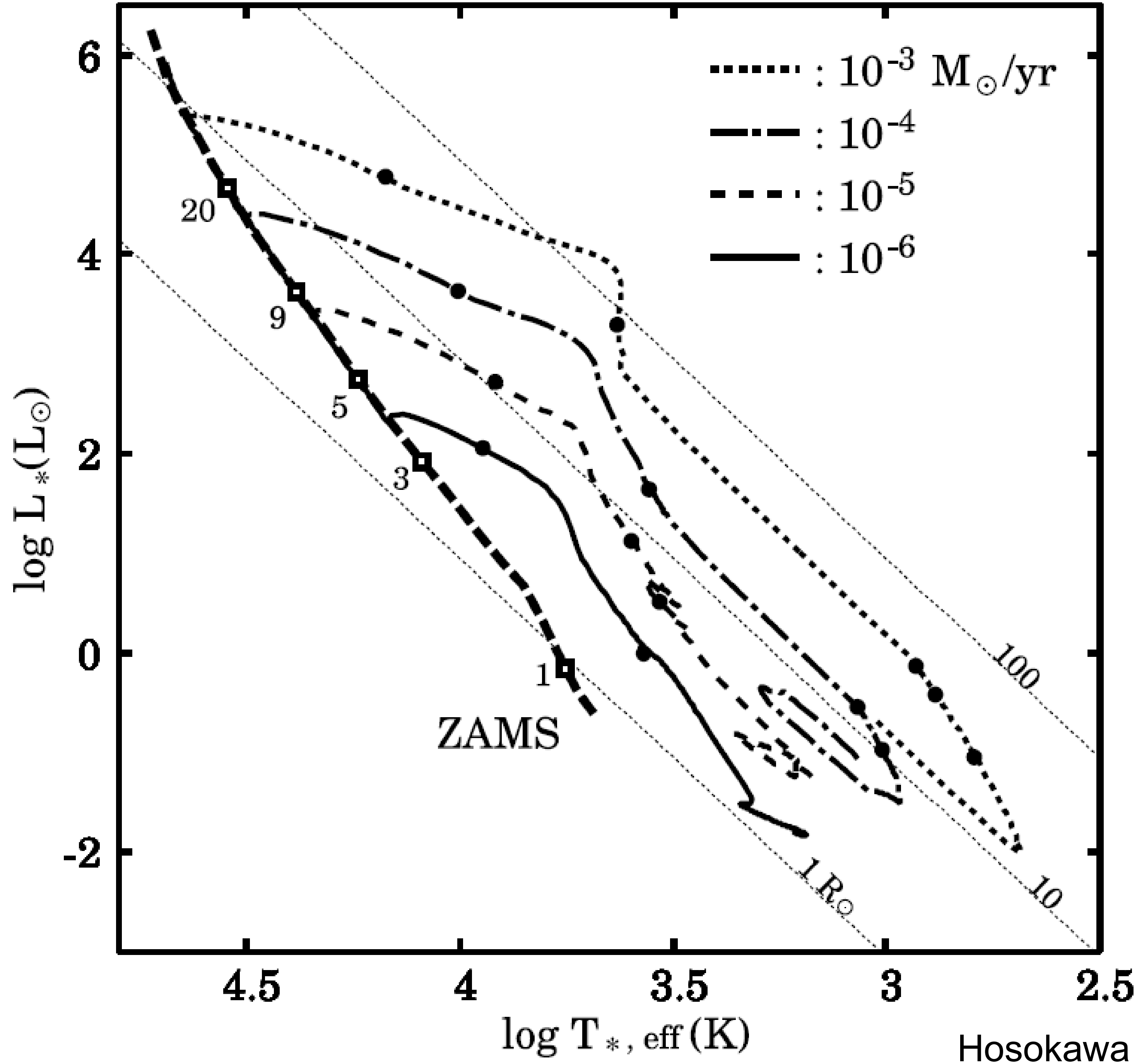


Disk accretion:
Yorke & Sonnenhalter (2002)

Stellar growth and accretion rate evolution for a 2-D HD collapse model with initial core mass of 60 $M_\odot$ and constant Planck opacities (solid) or fully frequency-dependent radiative transfer (dashed).

→ Full RT allows larger stellar mass (33$M_\odot$ vs. 20$M_\odot$)

Stellar evolution tracks for high accretion rates

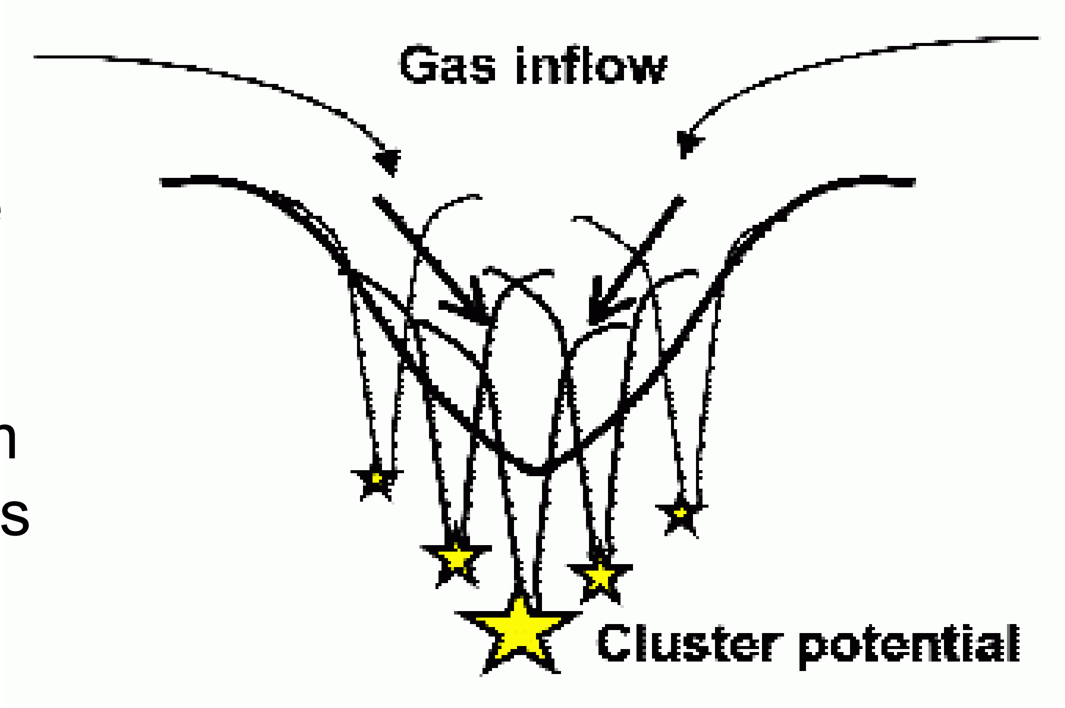


Hosokawa & Omukai 2009

Monolithic collapse?

Collapse of a 100 solar mass protostellar core to a massive star (Krumholz, Klein, & McKee 2007)

Competitive Accretion



- Already discussed in frame of IMF.

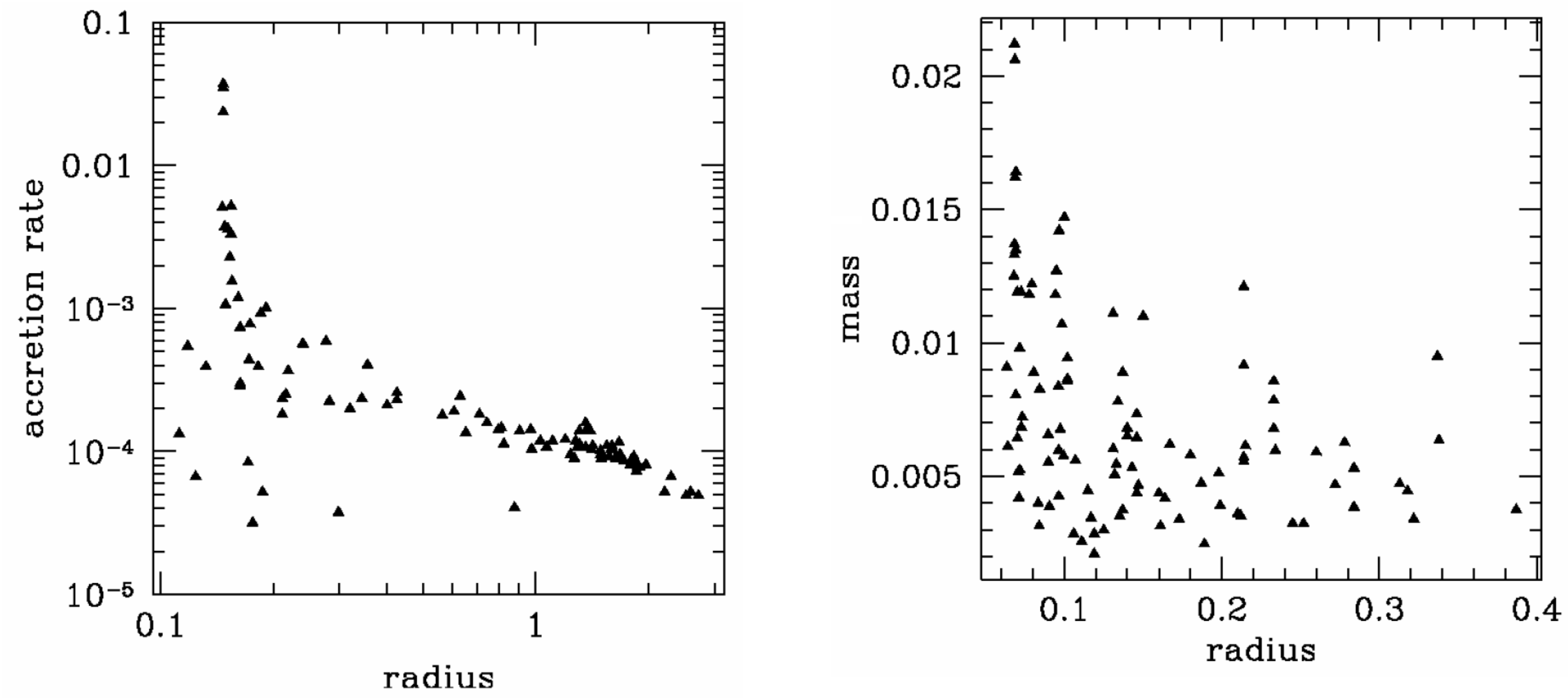
- Protostars accrete gas from the surroundings. Protostars at different positions in the cluster and with different mass compete for the remaining gas.

- The cluster members in the center of the gravitational potential are favoured, i.e. can pull matter from neighboring protostars.

Competitive accretion?

Protostars in cluster centers can accrete more mass

→ formation of higher mass stars



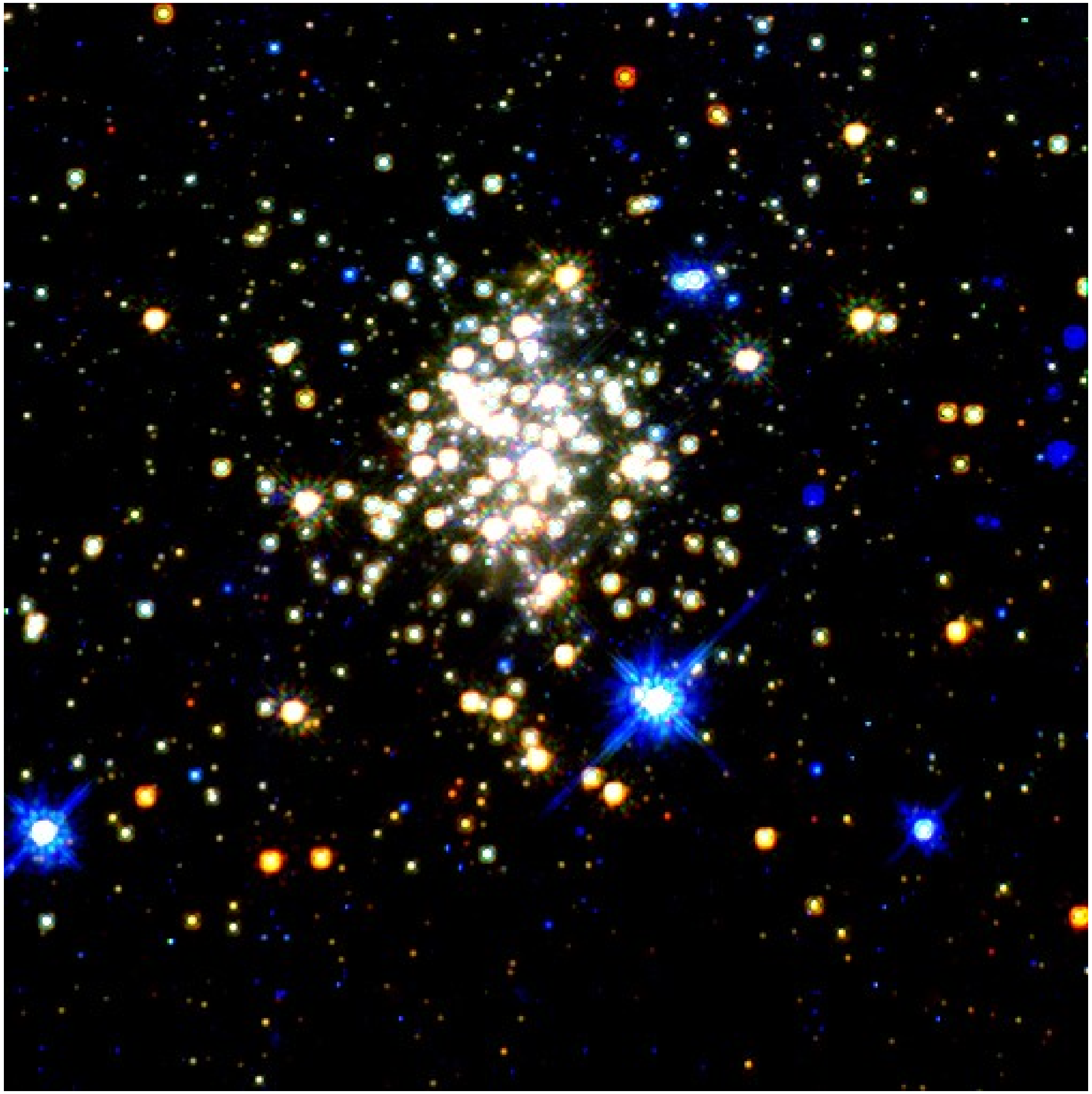
Accretion rate and resulting stellar mass (relative to the total gas mass) as function of radius from the cluster centre (Bonnell 2001).

Competitive accretion?

Coagulation model

Massive stars form in clusters.

Observational evidence shows that the most massive stars form close to the cluster core.



Arches cluster:

Age 2 Ma

Mass > $10^4 M_\odot$, > 160 O-stars

stellar density > $3 \times 10^5\ M_\odot\ \mathrm{pc}^{-3}$

→ Significant probability of stellar collisions in the centres of clusters!

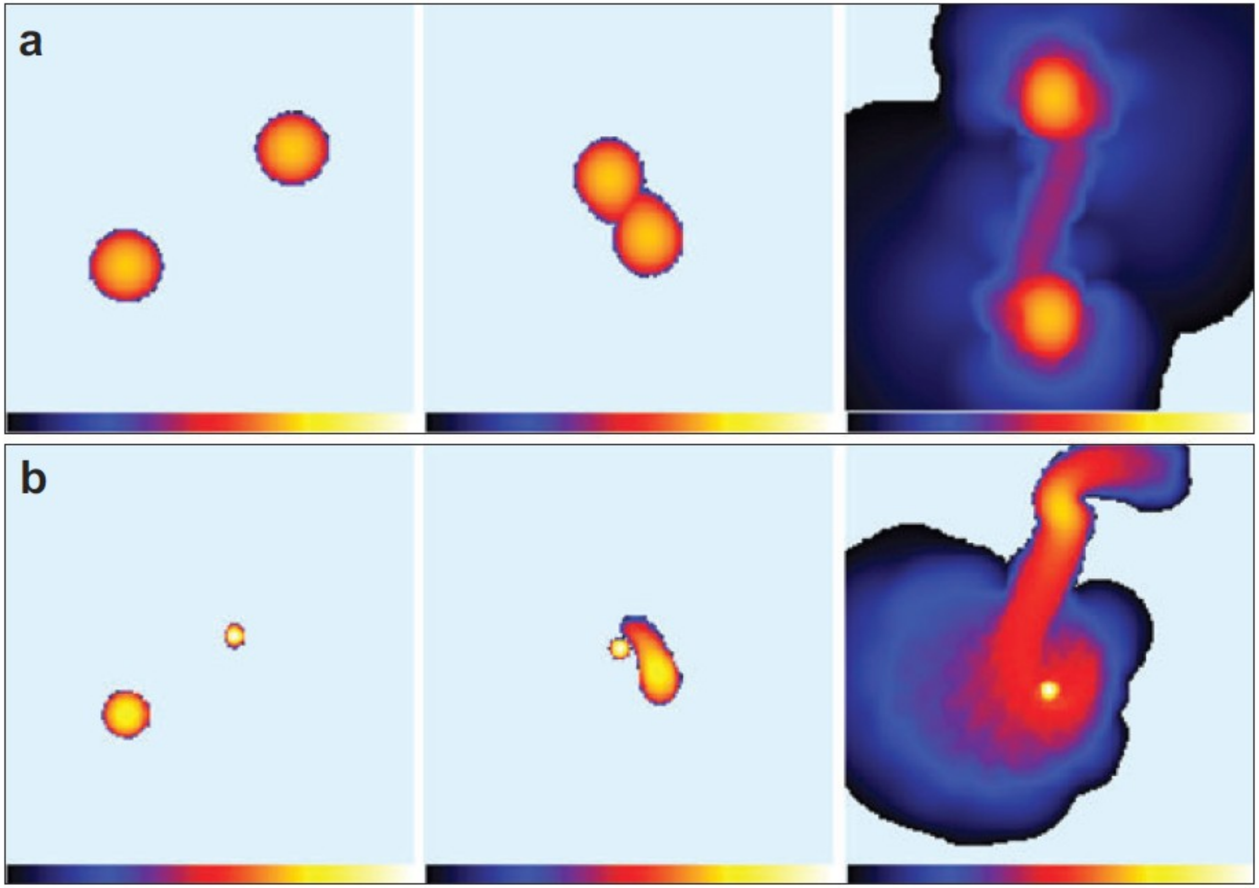
Coagulation model

In the coagulation model, stars with masses > 10 $M_\odot$ are formed by (proto)stellar mergers.

Grazing encounters:

a) two 3$M_\odot$ stars: formation of a binary system

b) 10$M_\odot$ star + 3$M_\odot$ star: the lower mass star is disrupted to form an accretion disk around the 10$M_\odot$ star



Zinnecker & Bate (2002)

Coagulation model

Quantitative analysis of the probability of stellar collisions in clusters:

Enhanced cross section due to gravitational focusing:

$$\sigma_{\mathrm{grav}} = \pi \mathrm{R}_{\mathrm{min}}^2 \left(1 + \frac{2\mathrm{GM}_*}{\mathrm{v}_\infty^2 \mathrm{R}_{\mathrm{min}}}\right)$$

Stellar collision time per star:

$$\tau_{\mathrm{coll}} = \frac{1}{\mathrm{n}_{\mathrm{star}}\, \sigma_{\mathrm{grav}}\, \mathrm{v}_{\mathrm{rms}}} = \left[4\sqrt{\pi}\,\mathrm{n}_{\mathrm{star}} \mathrm{v}_{\mathrm{rms}} \left(\mathrm{R}_{\mathrm{min}}\right)^2 \left(1 + \frac{2\mathrm{GM}_*}{\mathrm{R}_{\mathrm{min}} \mathrm{v}_{\mathrm{rms}}^2}\right)\right]^{-1},$$

If we assume that the gravitational focusing term dominates:

$$\tau_{\mathrm{coll}} = 7 \times 10^7 \left[\frac{\mathrm{n}_{\mathrm{star}}}{10^6\ \mathrm{pc}^{-3}}\right]^{-1} \left[\frac{\mathrm{M}_*}{10\ M_\odot}\right]^{-1} \left[\frac{\mathrm{R}_{\mathrm{min}}}{1\ R_\odot}\right]^{-1} \times \left[\frac{\mathrm{v}_{\mathrm{rms}}}{10\ \mathrm{km\,s}^{-1}}\right]\ \mathrm{a}$$

Dale & Davis (2006)

Coagulation model

In dense clusters collisions between stars can important:

- For very high stellar densities the time for collisions between (proto)stars is sufficiently short to allow for mergers.

- It is unclear if densities $> 10^8\,M_\odot\,pc^{-3}$ do exist.

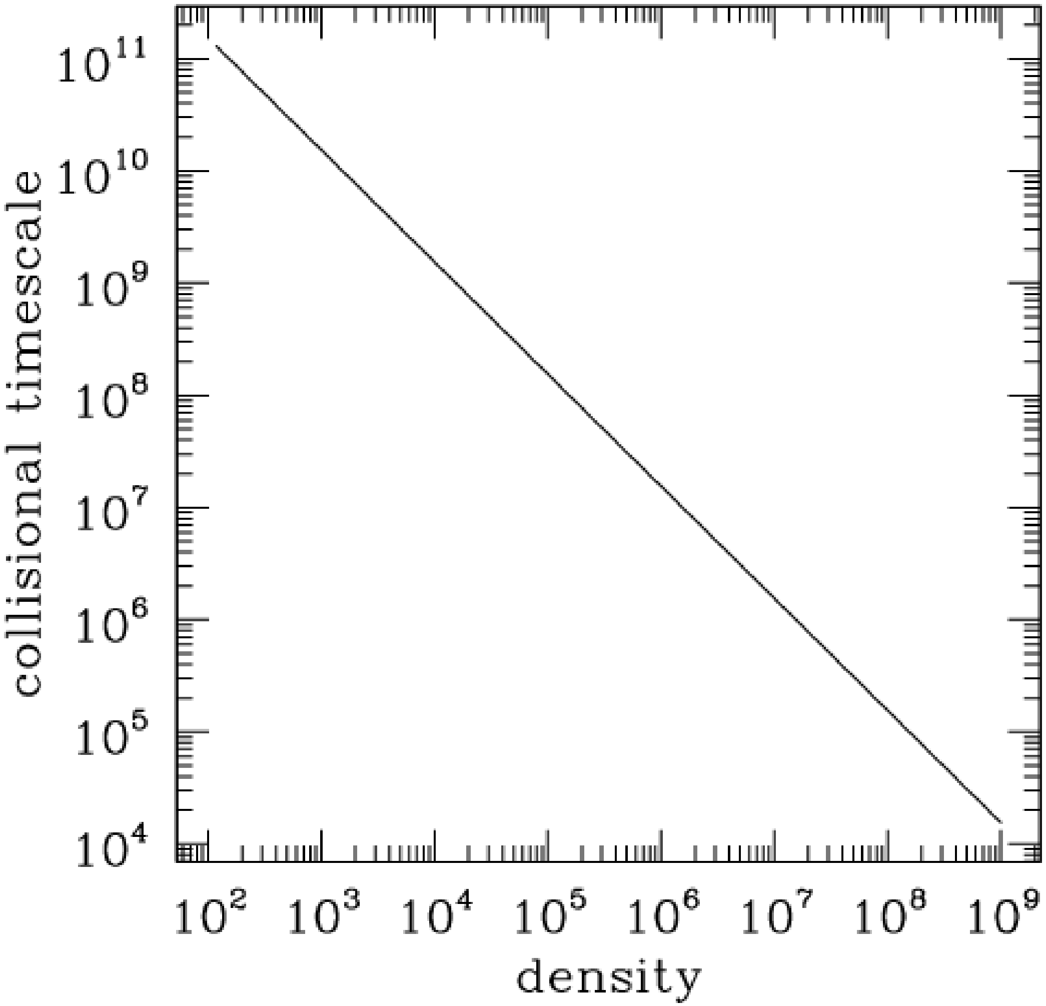


Figure 1. The collisional time-scale (in years) is plotted as a function of the density in a stellar cluster in star pc^{-3}. A velocity dispersion of 2 km s^{-1}, a stellar mass of 10 $M_\odot$ and a collisional radius of 10 $R_\odot$ are assumed.

Testable predictions:	**Status:**
• accretion models	
• accretion disks	candidates
• high accretion rates ($\gg 10^{-5}\ M_\odot$/yr)	evidence
• long, stable outflows	sometimes
• coagulation models	
• stellar collisions	not observed
• violent explosions	apparently
• disrupted disks	not observed
• fraction of binary stars high	yes
• extremely high stellar densities	no

We know very little about high mass star formation, and the earlier the stages, the less we know.

Observational approach

Hampered by practical problems:

Practical problems with investigating high mass stars

- very few
- short lifetime
- on the average far away
- cluster confuses observation

Problems with investigating high mass protostars:

- even fewer
- even shorter lifetime
- even larger average distance

but additionally

- enshrouded by dust: observable only in the mm/submm/FIR where
  - current instruments have less resolution than optical
  - it is difficult to observe from the ground
- protostars are bigger than stars: more confusion in clusters

Appearance of massive star forming regions

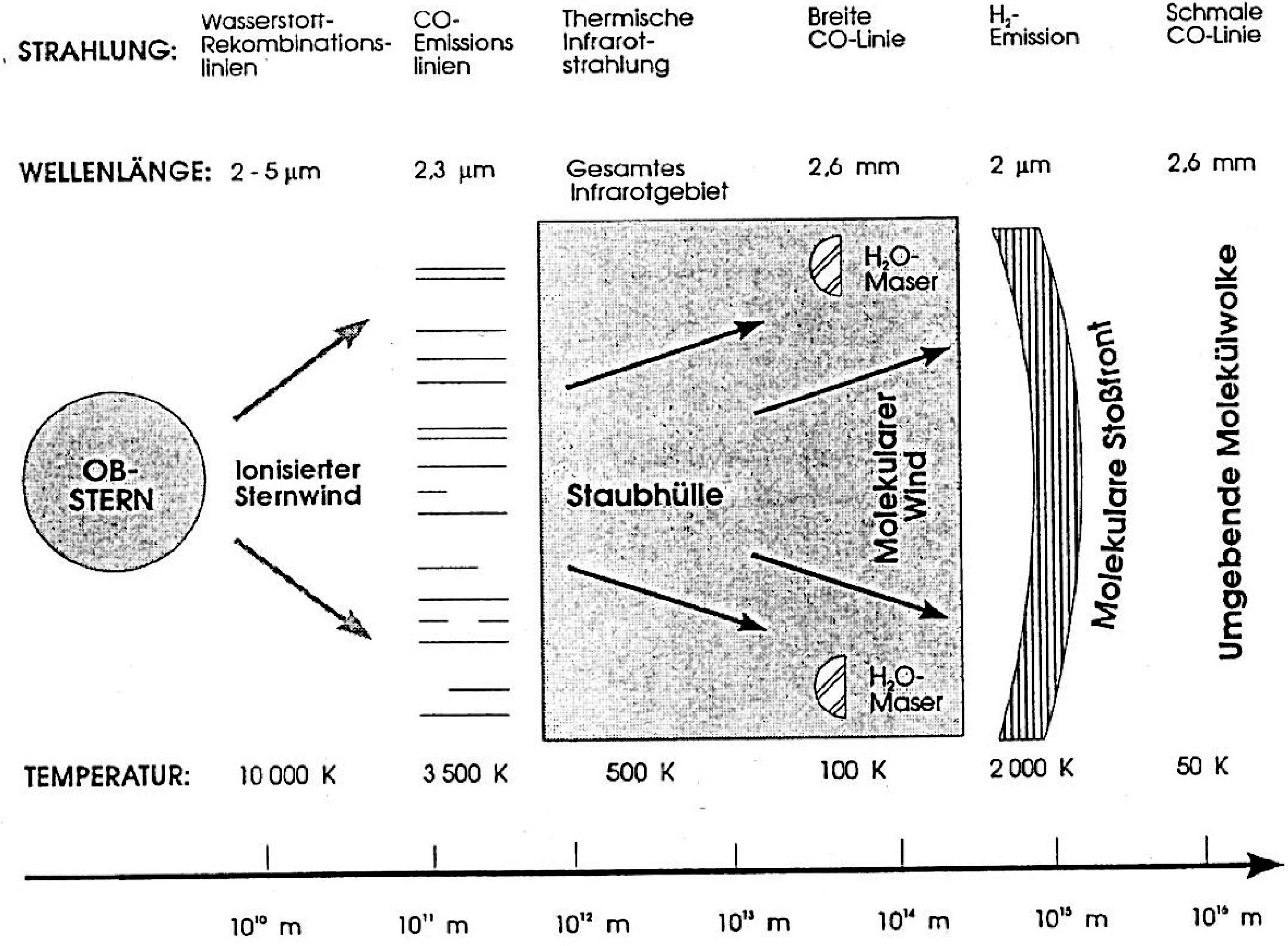
Infrared Dark Clouds massive, cold condensations
probably earliest phases of massive star formation
T(molecular gas) = 10 K (mm/submm emission)

High Mass Protostellar Object prior stage, considerable IR flux
embedded object, but no cm continuum yet
T(molecular gas) = 10-50 K (mm/submm emission)

Hot Cores prior stage, star emits in
the IR and warms up the cloud,
but the gas is still molecular
T(molecular gas) = 100-300 K (mm/submm/FIR emission)

UCHIIs star is already present and has
ionized its surroundings
T(HII) =10,000 K (centimeter radio emission)
T(molecular gas) =100-300 K (mm/submm/FIR emission)

What to look for?

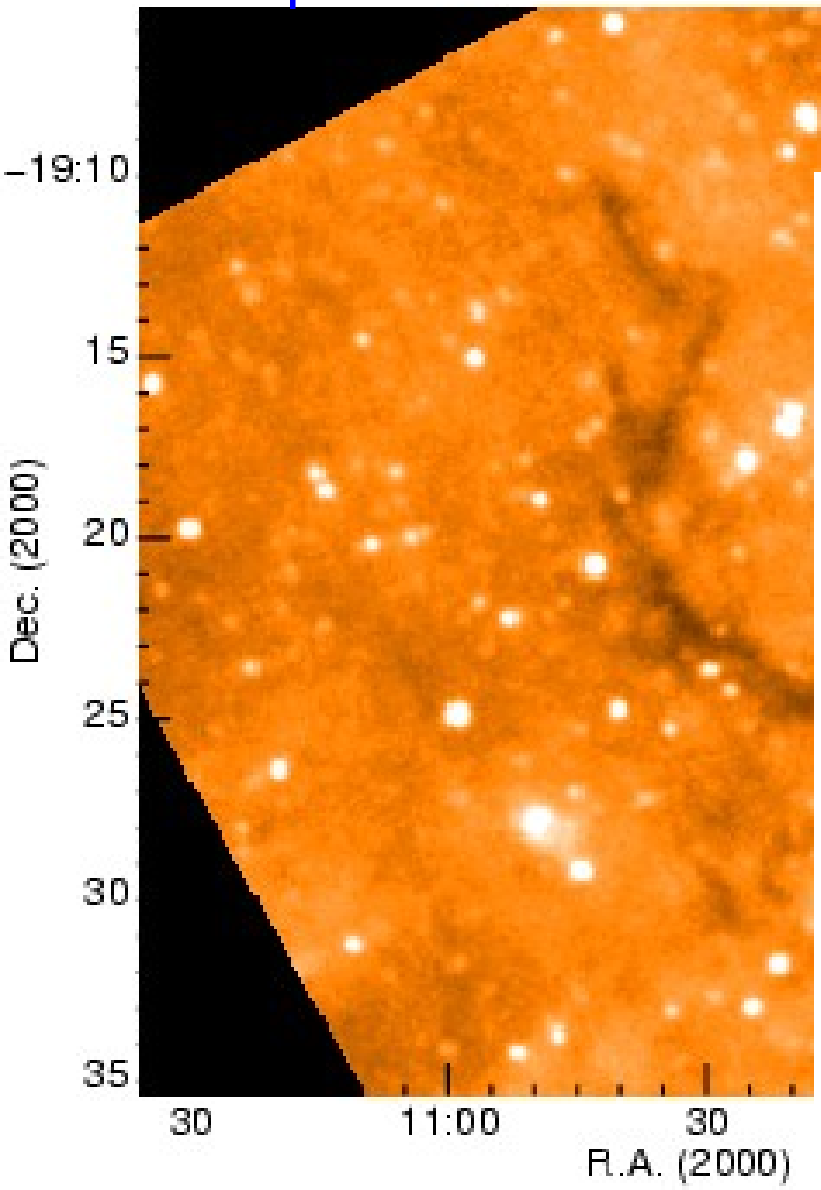


What to look for?

Wavelengths	Objects	Feasibility
X-rays	UCHIIs	Galactic and local extinction for all but the hardest X-rays, unclear emission strength
	IRDCs	no emission
optical, NIR (2 µm)	UCHIIs	Galactic and local extinction
	HCs, HMPOs, IRDCs	too cold
MIR (10-30 µm)	UCHIIs, HCs, HMPOs	Galactic and local extinction, atmosphere bad
	IRDCs	too cold, as shadows
FIR (50-200 µm)	UCHIIs, HCs, HMPOs, IRDCs	very good, but atmosphere blocks, IRAS low resolution
mm/submm	UCHIIs, HCs, HMPOs, IRDCs	very good, but no large scale surveys yet
Radio	UCHIIs	very good
	HCs, HMPOs	weak emission
	IRDCs	no emission

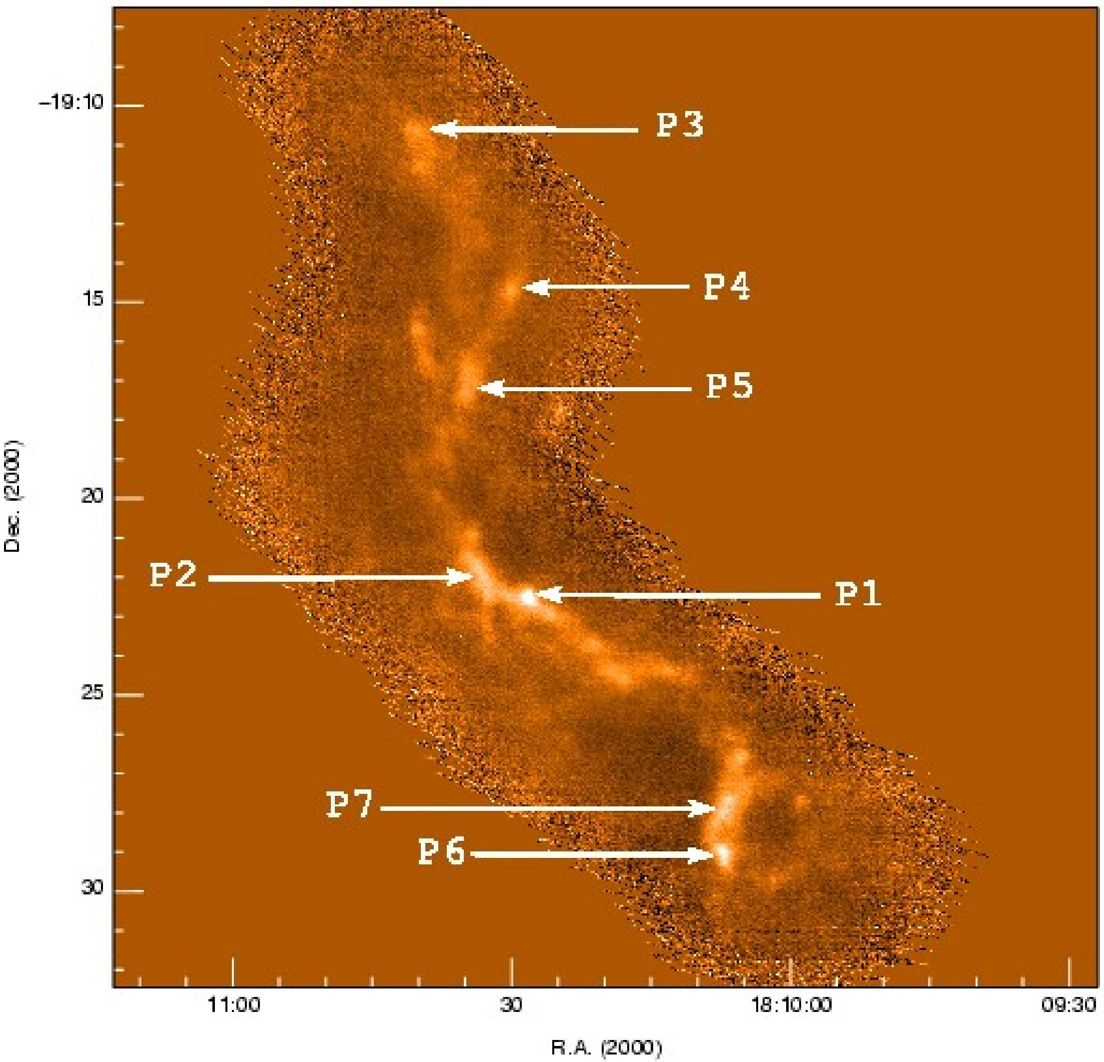
Infrared dark clouds

MSX 8 µm



Detected by
MSX, ISOCAM

SCUBA 870 µm

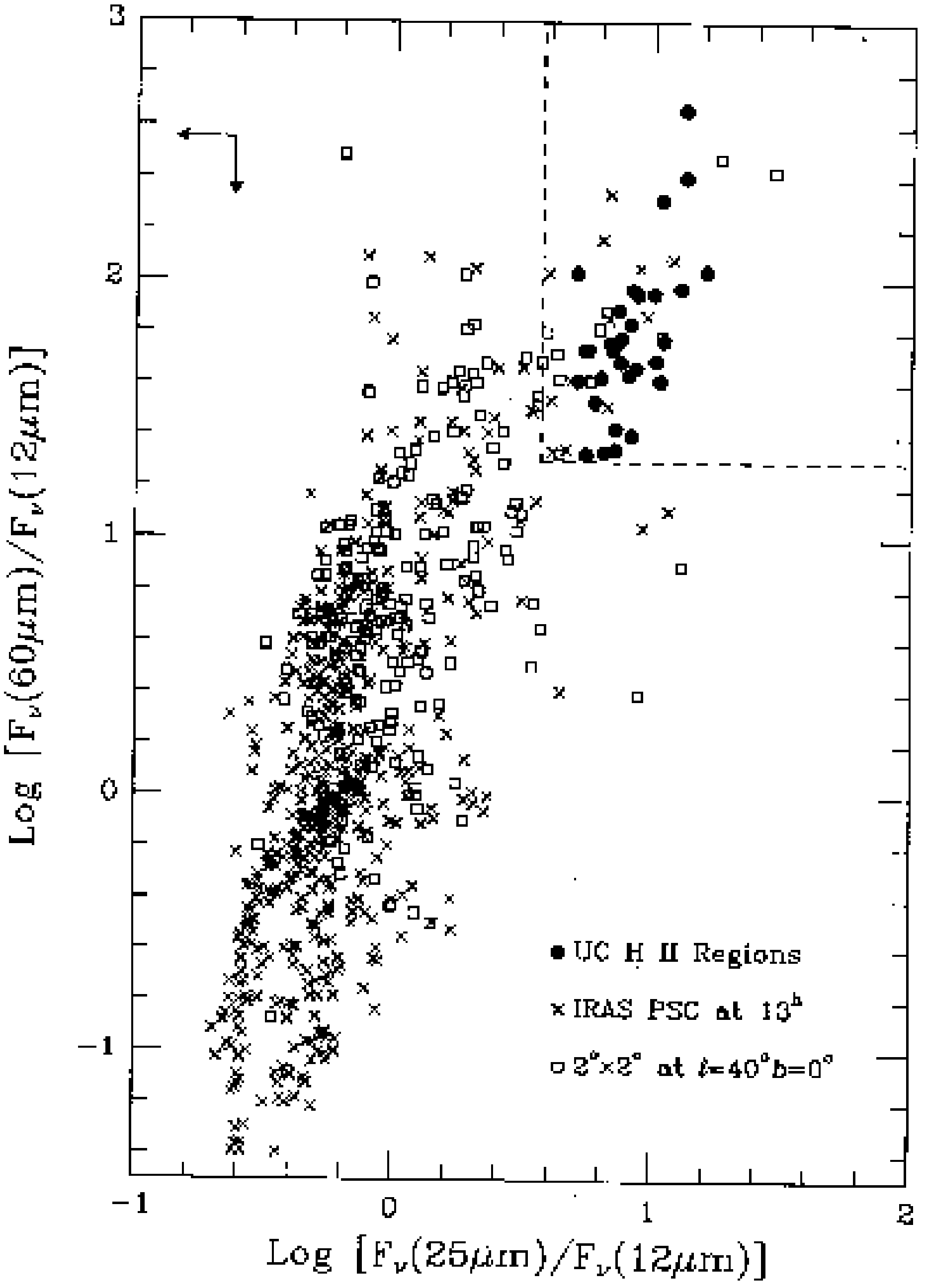


Search massive protostars by HIIs

Earliest stages difficult to observe:

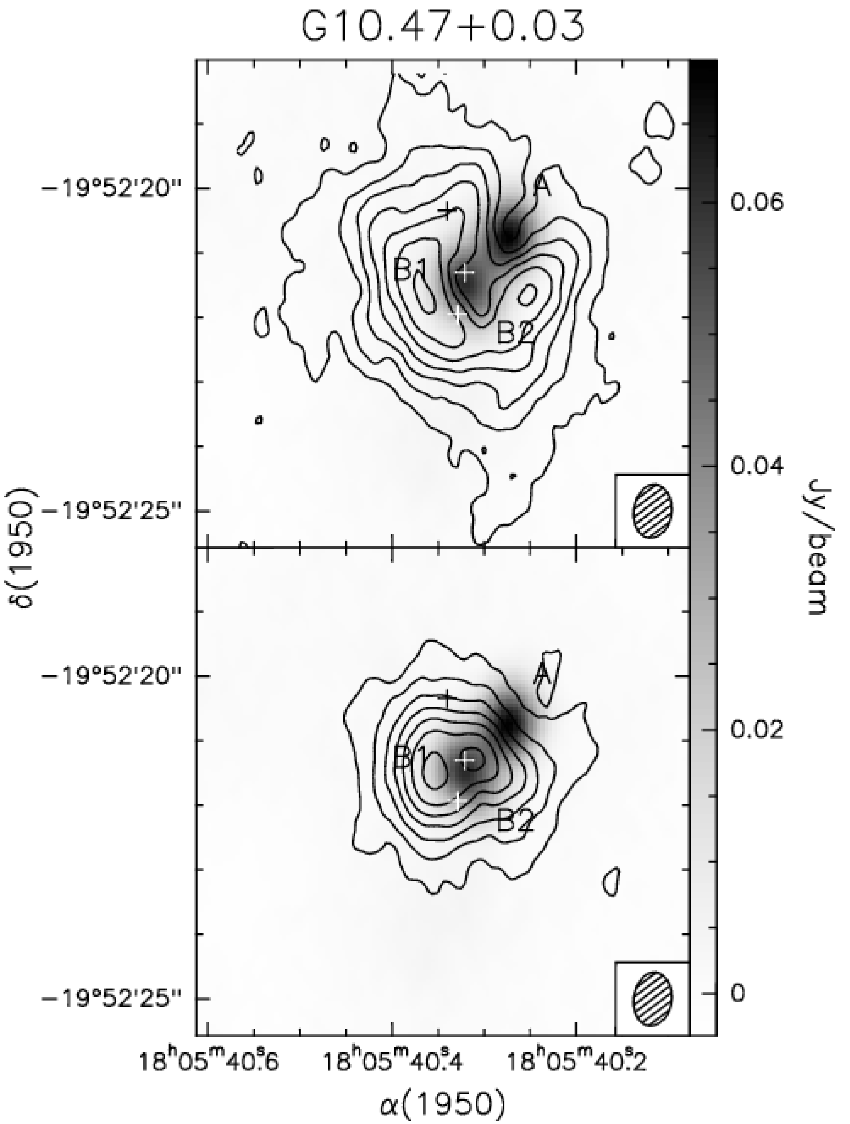
- earliest stage
  - flux of accreting particles exceeds flux of ionizing photons
  - HII region is quenched
- somewhat later
  - ionization flux increases, but infall velocity is still larger than sound speed in ionized gas
  - a trapped (hypercompact or ultracompact) HII region develops, which expands very slowly
- later stages
  - Once the radius of the HII region exceeds the sonic radius, hydrodynamic expansion starts with about 10 km/s
  - before the final Strömgren sphere is reached the star explodes as a supernova

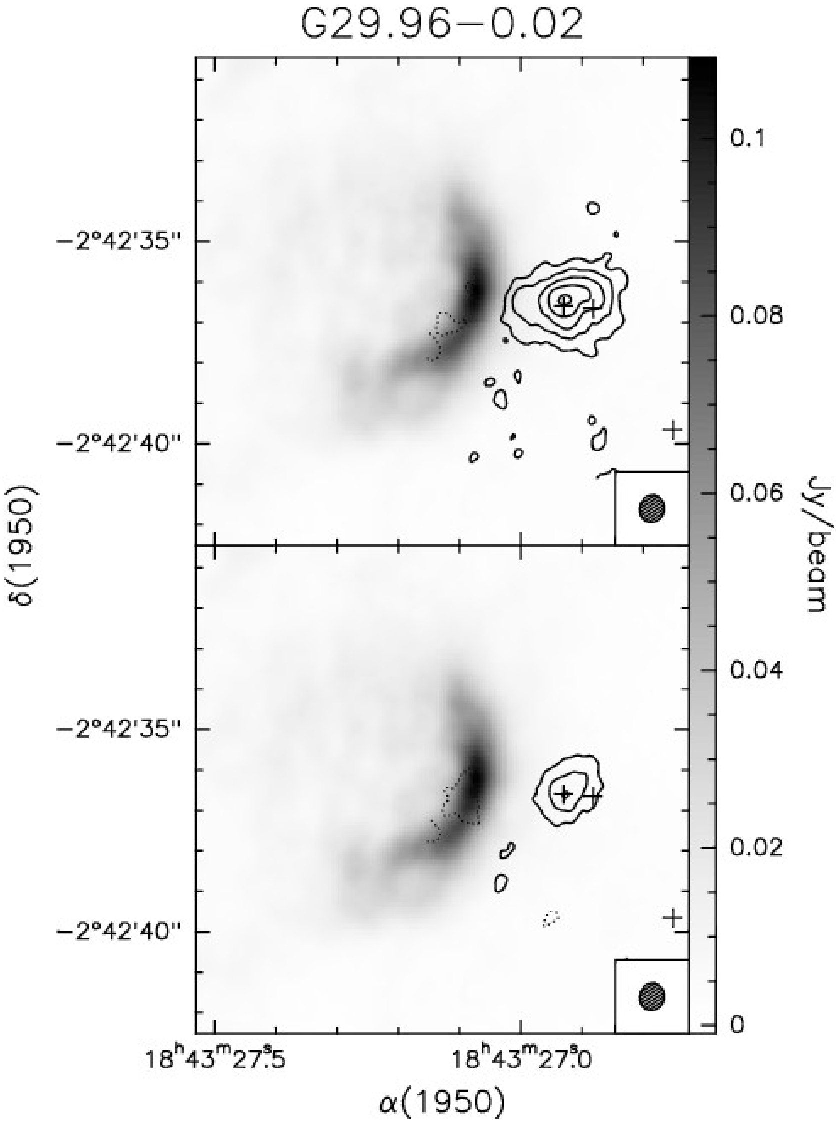
HII regions


1989ApJ...340..265W

Detection of UCHIIs based on IR colors (IRAS) of cores

UCHIIs and HCs: cm continuum (gray scale), NH_3 (contours)





Serendipitous detection of **hot cores** adjacent to UCHIIs:
→ consequence of clustered mode of star formation

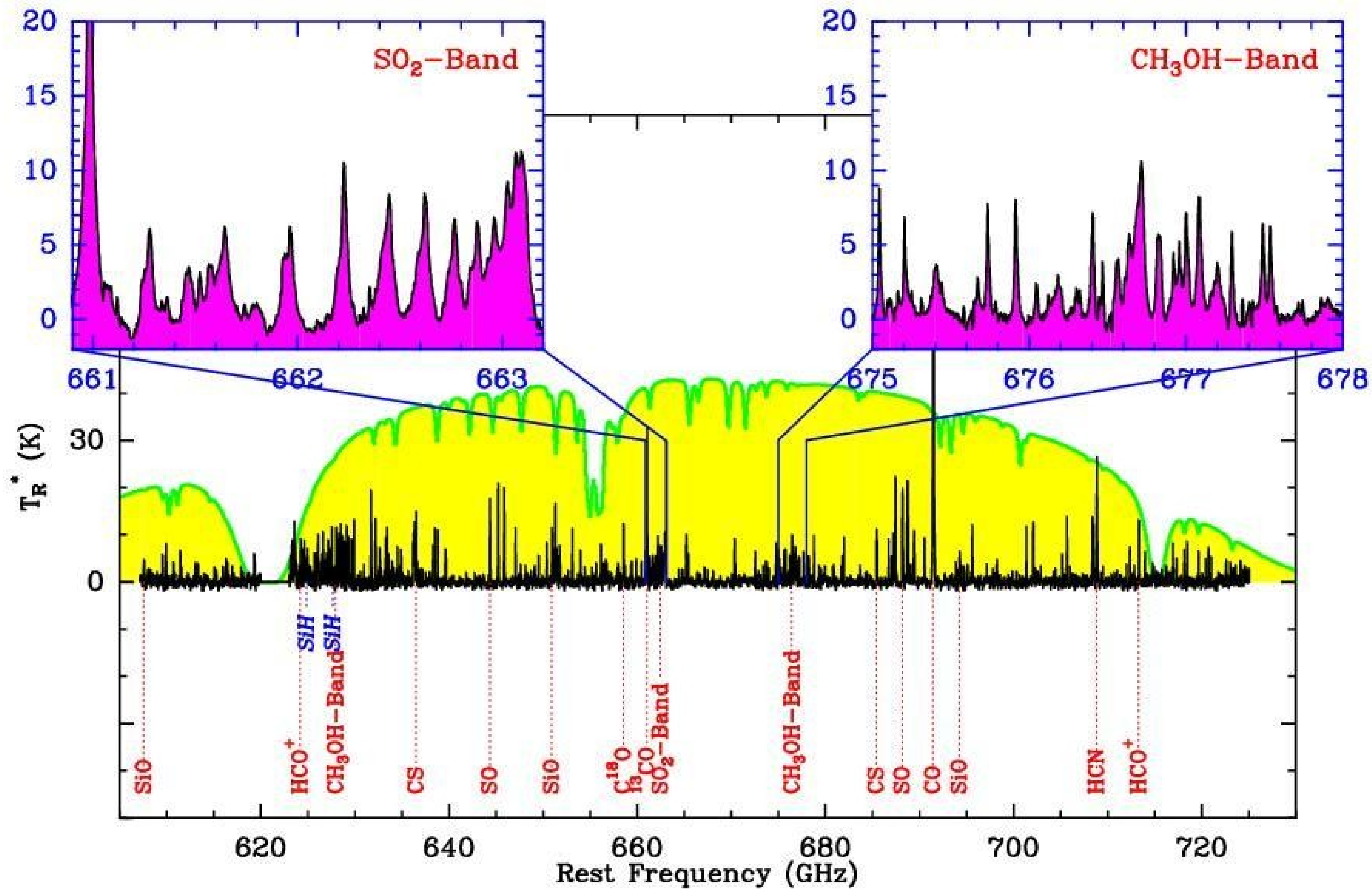
Hot cores

- harbor young stars
- no UV radiation (too early, quenching)
- lots of IR
- heat up gas
- evaporate ice mantles from dust grains accumulated during infall
- rapid gas phase chemistry in hot and dense gas

⇨very rich molecular spectra

Hot cores

⇨very rich molecular spectra



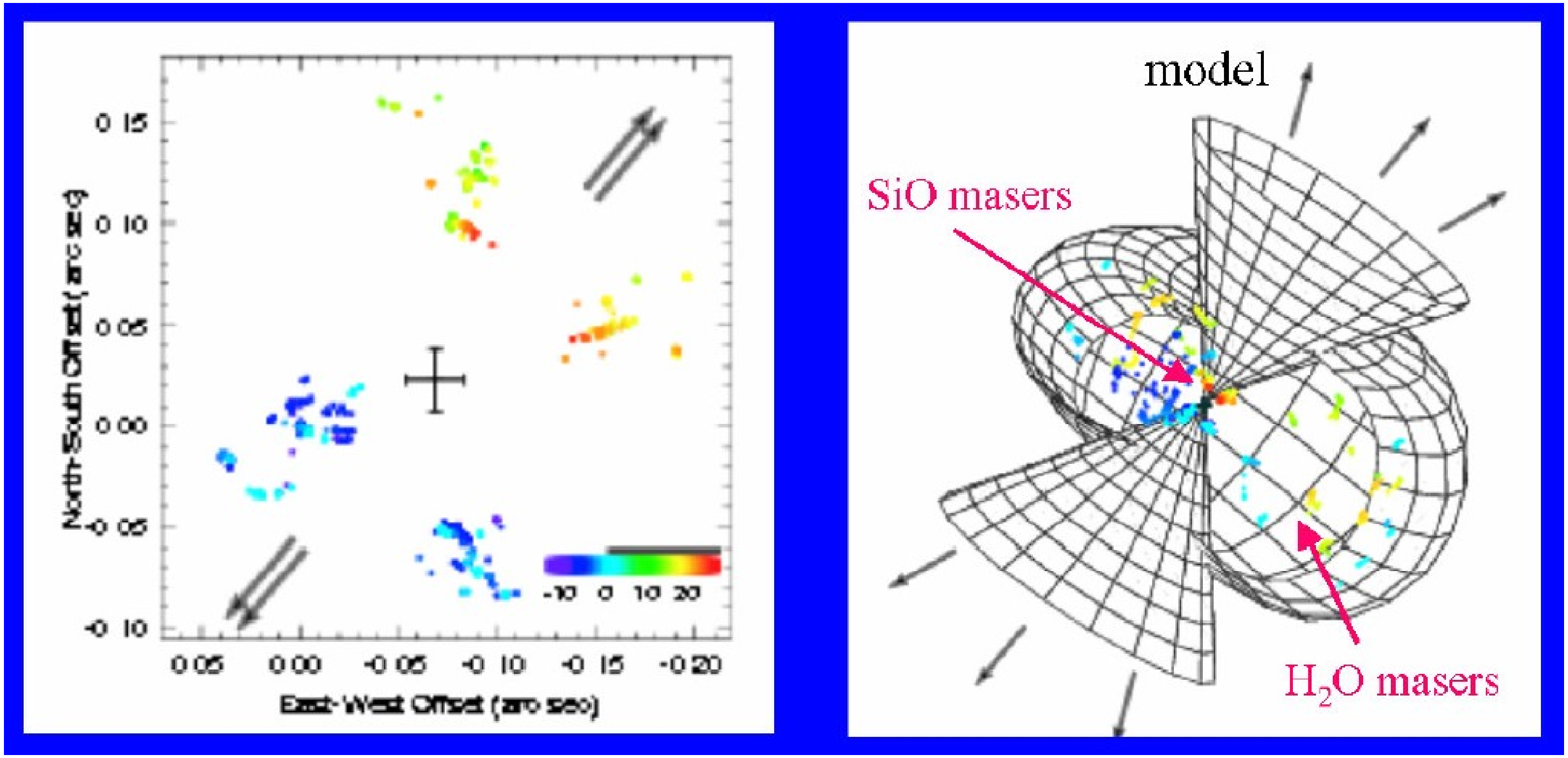
Masers

Masing lines observed to many HMPOs:

•Maser transitions pumped by bright IR continuum

•Requires combination of hot core-chemistry and bright continuum

•Allow to trace detailed dynamics in proper motion of maser spots



Masers in Orion Irc2:

- SiO maser in a torus at the disk surface
- H_2O maser in the outflow

Greenhill (1998)

So how do massive stars form?

Observational data still too incomplete, too sparse, too difficult to obtain, too complicated, regions too messy to give an answer!

evidence for accretion model

- high accretion rates
- collimated, stable outflows in some cases
- no fully monolithic collapse, but monolithic collapse elements in competitive accretion scenario

evidence for coalescence model

- explosion-like outflow at least in one case
- no collimated flows (yet!) in very massive protostellar objects
- probably only relevant in extremely dense clusters